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VOLUME II OF IV

SOIL, GROUND WATER AND SUBSURFACE GAS RELEASES

EPA 530/SW-87-001B

JULY 1987

DRAFT

WASTE MANAGEMENT DIVISION
OFFICE OF SOLID WASTE
U.S. ENVIRONMENTAL PROTECTION AGENCY

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This document, which is presented in four volumes, is intended to assist Regional and State personnel in exercising the discretion conferred by regulation in developing requirements for the conduct of RCRA Facility Investigations pursuant to 40 CFR 264. Instruction is provided for the development and performance of an investigation based on determinations made by the regulatory agency as expressed in the schedule of a permit or in an enforcement order order issued under HSWA Section 3008(h). The purpose of the RFI is to obtain information for fully characterize the nature and extent of releases of hazardous waste or constituents; This information will be used to determine whether interim corrective measures or a Corrective Measures Study will be necessary.

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ABSTRACT

On November 8, 1984, Congress enacted the Hazardous and Solid Waste Amendments (HSWA) to RCRA. Among the most significant provisions of HSWA are §3004(u), which requires corrective action for releases of hazardous waste or constituents from solid waste management units at hazardous waste treatment, storage and disposal facilities seeking final RCRA permits; and §3004(v), which compels corrective action for releases that have migrated beyond the facility property boundary. EPA will be promulgating rules to implement the corrective action provisions of HSWA, including requirements for release investigations and corrective measures.

This document, which is presented in four volumes, provides guidance to the owner or operator of hazardous waste management facilities as to the conduct of the second phase of the RCRA Corrective Action Program, the RCRA Facility Investigation (RFI). Instruction is provided for the development and performance of an investigation based on determinations made by the regulatory agency as expressed in the schedule of a permit or in an enforcement order issued under HSWA§3008(h). The purpose of the RFI is to obtain information to fully characterize the nature and extent of releases of hazardous waste or constituents. This information will be used to determine whether interim corrective measures or a Corrective Measures Study will be necessary.

DISCLAIMER

This Draft Report was prepared for the U.S. Environmental Protection Agency by the NUS Corporation, Waste Management Services Group, Gaithersburg, MD 20878, in fulfillment of Contract No. 68-01-7310, Work Assignment No. 5, and is based on previous work performed by Alliance Technologies, Inc., under Contract No. 68-01-6871. The opinions, findings, and conclusions expressed herein are those of the authors and not necessarily those of the U.S. Environmental Protection Agency or the cooperating agencies. Mention of company or product names is not to be considered an endorsement by the U.S. Environmental Protection Agency.

This document is intended to assist Regional and State personnel in exercising the discretion conferred by regulation in developing requirements for the conduct of RCRA Facility Investigations (RFIs) pursuant to 40 CFR 264. Conformance with this guidance is expected to result in the development of RFIs that meet the regulatory standard of adequately detecting and characterizing the nature and extent of releases. However, EPA will not necessarily limit acceptable RFIs to those that comport with the guidance set forth herein. This document is not a regulation (i.e., it does not establish a standard of conduct which has the force of law) and should not be used as such. Regional and State personnel must exercise their discretion in using this guidance document as well as other relevant information in determining whether an RFI meets the regulatory standard.

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RCRA FACILITY INVESTIGATION (RFI) GUIDANCE

VOLUME II

SOIL, GROUND WATER AND SUBSURFACE GAS RELEASES

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LIST OF ACRONYMS

AA - Atomic Absorption
AI - Soil Adsorption Isotherm Test
ASCS - Agricultural Stabilization and Conservation Service
ASTM - American Society for Testing and Materials
BCF - Bioconcentration Factor
BOD - Biological Oxygen Demand
CAG - EPA Carcinogen Assessment Group
CPF - Carcinogen Potency Factor
CBI - Confidential Business Information
CEC - Cation Exchange Capacity
CERCLA - Comprehensive Environmental Response, Compensation, and Lability Act
CFR - Code of Federal Regulations
CIR - Color Infrared
CM - Corrective Measures
CMI - Corrective Measures Implementation
CMS - Corrective Measures Study
COD - Chemical Oxygen Demand
COLIWASA - Composite Liquid Waste Sampler
DNPH - Dinitrophenyl Hydrazine
DO - Dissolved Oxygen
DOT - Department of Transportation
ECD - Electron Capture Detector
EM - Electromagnetic
EP - Extraction Procedure
EPA - Environmental Protection Agency
FEMA - Federal Emergency Management Agency
FID - Flame Ionization Detector
Foc - Fraction organic carbon in soil
FWS - U.S. Fish and Wildlife Service
GC - Gas Chromatography
GC/MS - Gas Chromatography/Mass Spectroscopy
GPR - Ground Penetrating Radar
HEA - Health and Environmental Assessment
HEEP - Health and Environmental Effects Profile
HPLC - High Pressure Liquid Chromatography
HSWA - Hazardous and Solid Waste Amendments (to RCRA)
HWM - Hazardous Waste Management
ICP - Inductively Coupled (Argon) Plasma
ID - Infrared Detector
Kd - Soil/Water Partition Coefficient
Koc - Organic Carbon Absorption Coefficient
Kow - Octanol/Water Partition Coefficient
LEL - Lower Explosive Limit
MCL - Maximum Contaminant Level
MM5 - Modified Method 5
MS/MS - Mass Spectroscopy/Mass Spectroscopy
NFIP - National Flood Insurance Program
NIOSH - National Institute for Occupational Safety and Health
NPDES - National Pollutant Discharge Elimination System
OSHA - Occupational Safety and Health Administration

LIST OF ACRONYMS (Continued)

OVA	-	Organic Vapor Analyzer
PID	-	Photo Ionization Detector
pKa	-	Acid Dissociation Constant
ppb	-	parts per billion
ppm	-	parts per million
PUF	-	Polyurethane Foam
PVC	-	Polyvinyl Chloride
QA/QC	-	Quality Assurance/Quality Control
RCRA	-	Resource Conservation and Recovery Act
RFA	-	RCRA Facility Assessment
RfD	-	Reference Dose
RFI	-	RCRA Facility Investigation
RMCL	-	Recommended Maximum Contaminant Level
RSD	-	Risk Specific Dose
SASS	-	Source Assessment Sampling System
SCBA	-	Self Contained Breathing Apparatus
SCS	-	Soil Conservation Service
SOP	-	Standard Operating Procedure
SWMU	-	Solid Waste Management Unit
TCLP	-	Toxicity Characteristic Leaching Procedure
TEGD	-	Technical Enforcement Guidance Document (EPA, 1986)
TOC	-	Total Organic Carbon
TOT	-	Time of travel
TOX	-	Total Organic Halogen
USGS	-	United States Geologic Survey
USLE	-	Universal Soil Loss Equation
UV	-	Ultraviolet
VOST	-	Volatile Organic Sampling Train
VSP	-	Verticle Seismic Profiling
WQC	-	Water Quality Criteria

SECTION 9

SOIL

9.1 Overview

The objective of an investigation of a release to soil is to characterize the nature, extent, and rate of migration of a release of hazardous waste or constituents to that medium. This section provides:

- A recommended strategy for characterizing releases to soils, which includes characterization of the source and the environmental setting of the release, and conducting a monitoring program that will characterize the release.
- Recommendations for data organization and presentation;
- Appropriate field methods that may be used in the investigation; and
- A checklist of information that may be needed for release characterization.

The exact type and amount of information required for sufficient release characterization will be site-specific and should be determined through interactions between the regulatory agency and the facility owner or operator during the RFI process. This guidance does not define the specific data needed in all instances; however, it identifies possible information that might be necessary to perform release characterizations and methods for obtaining this information. The RFI Checklist, presented at the end of this section, provides a tool for planning and tracking information for release characterization. This list is not meant to be a list of requirements for all releases to soil. Some release investigations will involve the collection of only a subset of the items listed, while others may involve the collection of additional data.

9.2 Approach for Characterizing Releases to Soil

9.2.1 General Approach

Characterizing contaminant releases to soils may employ a phased approach. Data collected during an initial phase can be evaluated to determine the need for or scope of subsequent efforts. For example, if a suspected release was identified by the regulatory agency, the initial monitoring effort may be geared to release verification. Table 9-1 presents a recommended release characterization strategy. The intensity and duration of the investigation will depend on the complexity of the environmental setting and the nature and magnitude (e.g., spatial extent and concentrations) of the release.

A preliminary task in any soil investigation should be to review existing site information that might help to define the nature and magnitude of the release. Information supplied by the regulatory agency in permit conditions or an enforcement order will indicate known or suspected releases to soil from specific units at the facility needing investigation; and may also indicate situations where inter-media contaminant transfer should be investigated.

The owner or operator should plan the initial characterization effort with all available information on the site, including wastes and soil characteristics. During the initial phase, constituents of concern as well as indicator parameters should be identified that can be used to characterize the release and determine the approximate extent and rate of migration of the release. Table 9-2 lists tasks that can be performed to characterize a release to soils and displays the associated techniques and outputs from each of these tasks. Soil characteristics and other environmental factors include 1) surface features such as topography, erosion potential, land-use capability, and vegetation; 2) stratigraphic/hydrologic features such as soil profile, particle size distribution, hydraulic conductivity, pH, porosity, and cation exchange capacity; and 3) meteorological factors such as temperature, precipitation, runoff, and evapotranspiration. Soil physical and chemical properties should be measured to determine the potential mobility of the contaminants in the

Table 9-1

Recommended Strategy for Characterizing Releases to Soil*

INITIAL PHASE

1. Collect and review preliminary information for use in formulating monitoring procedures:
   - Waste characterization
   - Unit characterization
   - Surface features and topography
   - Soil stratigraphy and hydrology
   - Meteorological conditions

2. Identify and collect additional information necessary to characterize release:
   - Waste and unit information
   - Soil characteristics and other environmental factors
   - Monitoring data
   - Inter-media transport
   - Formulate conceptual model of release

3. Develop monitoring procedures:
   - Determine monitoring program objectives
   - Select constituents and indicators to be monitored
   - Plan initial sampling based on site/waste/soil characteristics and conceptual model
   - Define study and background areas
   - Determine sampling methods, locations, depths and numbers
   - Sampling frequency
   - Analytical plans
   - QA/QC procedures

Table 9-1 (Continued)

Recommended Strategy for Characterizing Releases to Soil*

---

4. Conduct initial monitoring phase:

    - Conduct initial soil sampling and field measurements
    - Collect geologic data
    - Analyze samples for selected constituents and indicators

5. Collect, evaluate, and report results:

    - Compare monitoring results to health and environmental criteria and identify and respond to emergency situations and identify priority situations that may warrant interim corrective measures - Notify regulatory agency
    - Determine completeness and adequacy of collected data
    - Summarize and present data in an appropriate format
    - Determine if monitoring program objectives were met (e.g., monitoring locations, constituents and frequency were adequate to characterize release (nature, rate and extent)
    - Report results to regulatory agency

SUBSEQUENT PHASES (if necessary)

1. Identify additional information necessary to characterize release:

    - Identify additional information needs
    - Determine need to exand or include further soil stratigraphic and hydrologic sampling
    - Evaluate potential for inter-media contaminant transfer (e.g., leaching studies to evaluate potential for ground-water contamination)

2. Expand initial monitoring as necessary

    - Expand sampling area and/or density
    - Add or delete constituents and parameters of concern
    - Increase or decrease monitoring frequency

Table 9-1 (Continued)

Recommended Strategy for Characterizing Releases to Soil*

3. Conduct subsequent monitoring phases:

   - Perform expanded monitoring and field analyses
   - Analyze samples for selected constituents and parameters

4. Collect, evaluate, and report results/identify additional information necessary to characterize release:

   - Compare results to health and environmental criteria and identify and respond to emergency situations and identify priority situations that warrant interm corrective measures - Notify regulatory agency
   - Determine completeness and adequacy of collected data
   - Summarize and present data in appropriate format
   - Determine if monitoring program objectives were met
   - Determine if monitoring locations, constituents, and frequency were adequate to characterize release (nature, extent, and rate)
   - Determine need to expand monitoring system
   - Evaluate potential for inter-media contaminant transfer
   - Report results to regulatory agency

---

* The possibility for inter-media transport of contamination exists and should be anticipated throughout the investigation.

TABLE 9-2
RELEASE CHARACTERIZATION TASKS FOR SOILS

Investigatory Tasks	Investigatory Techniques	Data Presentation Formats/Outputs
1. Waste/Unit Characterization	- Refer to Sections 3 and 7	- Table of monitoring constituents and their chemical/physical properties - Table of unit features contributing to soil releases
2. Environmental Setting Characterization		
- Determine surface features and topography	- Aerial photography or mapping (See Appendix A	- Soil survey map Topographic map Photographs
- Characterize soil stratigraphy and hydrology	- Soil core examination	- Soil boring logs
	- Measurement of soil properties	- Soil profile, transpect, or fence diagram - Particle size distribution - Table of unsaturated hydraulic conductivities for each soil layer - Table of soil chemistry and structure (e.g., pH, porosity) for each soil type
- Meteorological Conditions	- On-site meteorological monitoring	- Temperature charts - Tables of monthly and annual precipitation, runoff, and evapotranspiration
3. Release Characterization	- Sampling and Analysis	- Map of sampling points - Table of constituent concentrations measured at each sampling point - Area and profile maps of site, showing distribution of contaminants
	- Soil Transport Modeling	- Table of input values, boundary conditions output values, and modeling assumptions - Maps of present or future extent of contamination

soil. Waste and soil properties should be examined to formulate a conceptual model of the release.

As monitoring data become available, both within and at the conclusion of discrete investigation phases, it should be reported to the regulatory agency as directed. The regulatory agency will compare the monitoring data to applicable health and environmental criteria to determine the need for (1) interim corrective measures; and (2) a Corrective Measures Study. In addition, the regulatory agency will evaluate the monitoring data with respect to adequacy and completeness to determine the need for any additional monitoring efforts. The health and environmental criteria and a general discussion of how the regulatory agency will apply them are supplied in Section 8. A flow diagram illustrating RFI decision points is provided in Section 3 (see Figure 3-2).

Not withstanding the above process, the owner or operator has a continuing responsibility to identify and respond to emergency situations and to define priority situations that may warrant interim corrective measures. For such situations, the owner or operator is directed to obtain and follow the RCRA Contingency Plan requirements under 40 CFR Part 264, Subpart D, and Part 265, Subpart D.

As indicated above, depending on the results of the initial phase, the need for further characterization will be determined by the regulatory agency. Subsequent phases, if necessary, may involve expansion of the sampling network, changes in the study area, investigation of contaminant transfer to other media, or other objectives dictated by the initial findings. The owner or operator may propose to use a mathematical model to aid in the choice of additional sampling locations or to estimate mobility in soil. The results of all characterization efforts should be organized and presented to the regulatory agency in a format appropriate to the data.

Case Study Numbers 1, 2, 3 and 17 in Volume IV (Case Study Examples) illustrate various aspects of soil investigations.

9.2.2 Inter-media Transport

As mentioned above, the potential for inter-media transfer of releases from the soil medium to other media is significant. Contaminated soil can be a major source of contamination to ground water, air, subsurface gas and surface water. Hazardous wastes or constituents, particularly those having a moderate to high degree of mobility, can leach from the soil to the ground water. Volatile wastes or constituents can contribute to subsurface gas and releases to air. Contaminated soils can also contribute to surface water releases, especially through run-off during heavy rains. Application of the universal soil loss equation (See Section 13.6) can indicate whether inter-media transport from soil to surface water as a result of erosion can act as a source of contamination. The owner or operator should recognize the potential for inter-media transport of releases to soil and should communicate as appropriate with the regulatory agency when such transport is suspected or identified during the investigation.

Similarly, the potential for inter-media transport of constituents from other media to the soil also exists. For example, hazardous waste or constituents may be transported to the soil via atmospheric deposition (especially during rain or snowfall events) through the air medium, and also through releases of subsurface gas. The guidance provided in this section addresses characterization of releases to soil from units and also can be used to characterize releases to soil as a result of inter-media transport through other media. A key to such characterization is determining the nature of the contaminant source, which is described in Section 9.3.

It is also important to recognize that where multiple media appear to be contaminated, the investigation can be coordinated to provide results that can apply to more than one of the affected media. For example, soil-gas analysis (using an organic vapor analyzer along with the subsurface investigation) can be used to investigate releases to soil and subsurface gas releases, and may also provide information concerning the spatial extent of contaminated ground water.

9.3 Characterization of the Contaminant Source and the Environmental Setting

9.3.1 Waste Characterization

The physical and chemical properties of the waste or its constituents affect their fate and transport in soil; and, therefore affect the selection of sampling and analytical methods. Identification of monitoring constituents and the use of indicator parameters is discussed in Section 3 and Appendix B. Sources of information and sampling techniques for determining waste characteristics are discussed in detail in Section 7.

Chemicals released to soil may undergo transformation or degradation by chemical or biological mechanisms, may be adsorbed onto soil particles, or may volatilize into soil pore spaces or into the air. Table 9-3 summarizes various physical, chemical, and biological transformation/transport processes that affect waste and waste constituents in soil.

The chemical properties of the contaminants of concern also influence the choice of sampling method. Important considerations include the water solubility and volatility of the contaminants, and the potential hazards to equipment and operators during sampling. For example, water soluble compounds that are mobile in soil water can be detected by pore water sampling and whole soil sampling. Volatile organic contaminants require specialized sampling and sample storage measures to prevent losses prior to analysis. Viscous substances require different sampling techniques due to their physical properties.

Reactive, corrosive, or explosive wastes may pose a potential hazard to personnel during soil sampling. High levels of organic contamination may also cause health problems due to toxicity. For example, landfills can produce methane gas that can explode if ignited by sparks or heat from the drilling operation. Corrosive, reactive, or explosive wastes can also damage soil sampling equipment or cause fires and explosions. Appropriate precautions to prevent such incidents include having an adequate health and safety plan in place, using explosimeters or organic vapor detectors as early-warning devices, and employing geophysical techniques to help identify buried objects (e.g., to locate buried drums). All

TABLE 9-3
TRANSFORMATION/TRANSPORT PROCESSES IN SOIL

Process	Key Factor
Biodegradation	Waste degradability Waste toxicity Acclimation of microbial community Aerobic/anaerobic conditions pH Temperature Nutrient concentrations
Photodegradation	Solar irradiation Exposed surface area
Hydrolysis	Functional group of chemical Soil pH and buffering capacity Temperature
Oxidation/reduction	Chemical class of contaminant Presence of oxidizing agents
Volatilization	Partial pressure Henry's Law Constant Soil diffusion Temperature
Adsorption	Effective surface area of soil Cation exchange capacity (CEC) Fraction organic content (f_{oc}) of soil Octanol/water partition coefficient (k_{ow})
Dissolution	Solubility Soil pH and buffering capacity Complex formation

contaminated soil samples should be handled as if they contain dangerous levels of hazardous wastes or constituents.

Identity and composition of contaminants--The owner or operator should identify and provide approximate concentrations for any constituents of concern found in the original waste and, if available, in leachate from any releasing unit. Identification of other (non-hazardous) waste components that may affect the behavior of hazardous constituents or may be used as indicator parameters is also recommended. Such components may form a primary leachate causing transport behavior different from water and may also mobilize hazardous constituents bound to the soil. Estimations of transport behavior can help to focus the determination of sampling locations.

Physical state of contaminants--The physical state (solid, liquid, or gas) of the contaminants in the waste and soil should be determined by inspection or from site operating records. Sampling can then be performed in locations most likely to contain the contaminant.

Viscosity--The viscosity of any bulk liquid wastes should be determined to estimate potential mobility in soils. A liquid with a lower viscosity will generally travel faster than one of a higher viscosity.

pH--Bulk liquid pH may affect contaminant transport in at least two ways: (1) it may alter the chemical form of acids and bases, metal salts, and other metal complexes, thereby altering their water solubility and soil sorption properties, and (2) it may alter the soil chemical or physical makeup, leading to changes in sorptive capacity or permeability. For example, release of acidic (low pH) wastes in a karst (e.g., limestone) environment can lead to the formation of solution channels. See Section 10.3 for more information on karst formations.

Dissociation constant (pKa)--For compounds that are appreciably ionized within the expected range of field pH values, the pKa of the compound should be determined. Ionized compounds have either a positive or negative charge and are often highly soluble in water; therefore, they are generally more mobile than in their neutral forms when dissolved. Compounds that may ionize include organic and inorganic acids and bases, phenols, metal salts, and other inorganic complexes.

Estimated contaminant concentration isopleths can be plotted with this information and can be used in determining sampling locations.

Density--The density of major waste components should be determined, especially for liquid wastes. Components with a density greater than water, such as some chlorinated solvents, may migrate through soil layers more quickly than components less dense than water, such as gasoline.

Water solubility--This chemical property influences constituent mobility and sorption of chemicals to soil particle surfaces. Highly water-soluble compounds are generally very mobile in soil and ground water. Liquid wastes that have low solubility in water may form a distinct phase in the soil with flow behavior different from that of water. Additional sampling locations may be needed to characterize releases of insoluble species.

Henry's Law constant--This parameter indicates the partitioning ratio of a chemical between air and water phases at equilibrium. The larger the value of a constituent's Henry's Law Constant, the greater is it's tendency to volatilize from water surrounding soil particles into soil pore spaces or into above-ground air. The Henry's Law Constant should be considered in assessing the potential for inter-media transport of constituents in soil gas to the air. Therefore, this topic is also discussed in the Air and Subsurface Gas sections (Section 11 and 12, respectively). Information on this parameter can help in determining which phases to sample in the soil investigation.

Octanol/Water partition coefficient (k_{ow})--The characteristic distribution of a chemical between an aqueous phase and an organic phase (octanol) can be used to predict the sorption of organic chemicals onto soils. It is frequently expressed as a logarithm (log k_{ow}). In transport models, k_{ow} is frequently converted to k_{oc}, a parameter that takes into account the organic content of the soil. The empirical expression used to calculate k_{oc} is: $k_{oc} = 0.63\, k_{ow} f_{oc}$, where f_{oc} is the fraction by weight of organic carbon in the soil. The higher the value of k_{ow} (or k_{oc}) the greater the tendency of a constituent to adsorb to soils containing appreciable organic carbon. Consideration of this parameter will also help in determining which phases to sample in the soil investigation.

Biodegradability--There is a wide variety of microorganisms that may be present in the soil. Generally, soils that have significant amounts of organic matter will contain a higher microbial population, both in density and in diversity. Microorganisms are responsible for the decay and/or transformation of organic materials and thrive mostly in the "A" (uppermost) soil horizon where carbon content is generally highest and where aerobic digestion occurs. Since some contaminants can serve as organic nutrient sources that soil microorganisms will digest as food, these contaminants will be profoundly affected within organic soils. Digestion may lead to complete decomposition, yielding carbon dioxide and water, but more often resulting in partial decomposition and transformation into other substances. Transformation products will likely have different physical, chemical or toxicological characteristics than the original contaminants. These products may also be hazardous constituents and should therefore be considered in developing monitoring programs. The decomposition or degradation rate depends on various factors, including:

- The molecular structure of the contaminants. Certain manmade compounds (e.g., PCBs and chlorinated pesticides) are relatively nondegradable (or persistent), whereas others (e.g., methyl alcohol) are rapidly consumed by bacteria. The owner or operator should consult published lists of compound degradability such as Table 9-4 to determine the persistence of waste constituents in soil. This table provides relative degradabilities for some organic compounds and can be used to identify appropriate monitoring constituents and indicator parameters. It may be especially useful for older releases where degradation may be a significant factor. For example, some of the parent compounds that are relatively degradable (see Table 9-4) may have been reduced to carbon dioxide and water or other decomposition products prior to sampling. Additional information on degradability can be found in Elliott and Stevenson, 1977, Sims et al, 1984, and U.S. EPA, 1985. See Section 9.8 for complete citations for these references.

- Moisture content. Active biodegradation does not generally occur in relatively dry soils or in some types of saturated soils, such as those that are saturated for long periods of time, as in a bog.

TABLE 9-4. BOD$_5$/COD RATIOS FOR VARIOUS ORGANIC COMPOUNDS*

Compound	Ratio	Compound	Ratio
RELATIVELY UNDEGRADABLE		**MODERATELY DEGRADABLE (CONT'D)**	
Butane	~0	Mineral spirits	~0.02
Butylene	~0	Cyclohexanol	0.03
Carbon tetrachloride	~0	Acrylonitrile	0.031
Chloroform	~0	Nonanol	>0.033
1,4-Dioxane	~0	Undecanol	<0.04
Ethane	~0	Methylethylpyridine	0.04-0.75
Heptane	~0	1-Hexene	<0.044
Hexane	~0	Methyl isobutyl ketone	<0.044
Isobutane	~0	Diethanolamine	<0.049
Isobutylene	~0	Formic acid	0.05
Liquefied natural gas	~0	Styrene	>0.06
Liquefied petroleum gas	~0	Heptanol	<0.07
Methane	~0	sec-Butyl acetate	0.07-0.23
Methyl bromide	~0	n-Butyl acetate	0.07-0.24
Methyl chloride	~0	Methyl alcohol	0.07-0.73
Monochlorodifluoromethane	~0	Acetonitrile	0.079
Nitrobenzene	~0	Ethylene glycol	0.081
Propane	~0	Ethylene glycol monoethyl ether	<0.09
Propylene	~0	Sodium cyanide	<0.09
Propylene oxide	~0	Linear alcohols (12-15 carbons)	>0.09
Tetrachloroethylene	~0	Allyl alcohol	0.091
Tetrahydronaphthalene	~0	Dodecanol	0.097
1 Pentrene	<0.002	**RELATIVELY DEGRADABLE**	
Ethylene dichloride	0.002	Valeraldehyde	<0.10
1 Octene	>0.003	n-Decyl alcohol	>0.10
Morpholine	<0.004	p-Xylene	<0.11
Ethylenediaminetetracetic acid	0.005	Urea	0.11
Triethanolamine	<0.006	Toluene	<0.12
o-Xylene	<0.008	Potassium cyanide	0.12
m-Xylene	<0.008	Isopropyl acetate	<0.13
Ethylbenzene	<0.009	Amyl acetate	0.13-0.34
MODERATELY DEGRADABLE		Chlorobenzene	0.15
Ethyl ether	0.012	Jet fuels (various)	~0.15
Sodium alkylbenzenesulfonates	~0.017	Kerosene	~0.15
Monoisopropanolamine	<0.02	Range oil	~0.15
Gas oil (cracked)	~0.02	Glycerine	<0.16
Gasolines (various)	~0.02	Adiponitrile	0.17

TABLE 9-4. (Continued)

Compound	Ratio	Compound	Ratio
RELATIVELY DEGRADABLE (CONT'D.)		**RELATIVELY DEGRADABLE (CONT'D.)**	
Furfural	0.17-0.46	Ethyleneimine	0.46
2-Ethyl-3-propylacrolein	<0.19	Monoethanolamine	0.46
Methylethylpyridine	<0.20	Pyridine	0.46-0.58
Vinyl acetate	<0.20	Dimethylformamide	0.48
Diethylene glycol monomethyl ether	<0.20	Dextrose solution	0.50
Napthalene (molten)	<0.20	Corn syrup	~0.50
Dibutyl phthalate	0.20	Maleic anhydride	>0.51
Hexanol	~0.20	Propionic acid	0.52
Soybean oil	~0.20	Acetone	0.55
Paraformaldehyde	0.20	Aniline	0.56
n-Propyl alcohol	0.20-0.63<0.24	Isopropyl alcohol	0.56
Methyl methacrylate	<0.24	n-Amyl alcohol	0.57
Acrylic acid	0.26	Isoamyl alcohol	0.57
Sodium alkyl sulfates	0.30	Cresols	0.57-0.68
Triethylene glycol	0.31	Crotonaldehyde	<0.58
Acetic acid	0.31-0.37	Phthalic anhydride	0.58
Acetic anhydride	>0.32	Benzaldehyde	0.62
Ethylenediamine	<0.35	Isobutyl alcohol	0.63
Formaldehyde solution	0.35	2,4-Dichlorophenol	0.78
Ethyl acetate	<0.36	Tallow	~0.80
Octanol	0.37	Phenol	0.81
Sorbitol	<0.38	Benzoic acid	0.84
Benzene	<0.39	Carbolic acid	0.84
n-Butyl alcohol	0.42-0.74	Methyl ethyl ketone	0.88
Propionaldehyde	<0.43	Benzoyl chloride	0.94
n-Butyraldehyde	<0.43	Hydrazine	1.0
		Oxalic acid	1.1

*Source: U.S. EPA 1985. Handbook: Remedial Action at Waste Disposal Sites (Revised). EPA/625/6-85/006. NTIS PB82-239054. Office of Emergency and Remedial Response. Washington, D.C. 20460.

- The presence or absence of oxygen in the soil. Most degradable chemicals decompose more rapidly in aerobic (oxygenated) soil. Although unsaturated surficial soils are generally aerobic, anaerobic conditions may exist under landfills or other units. Soils that are generally saturated year round are relatively anaerobic (e.g., as in a bog); however, most saturated soils contain enough oxygen to support active biodegradation. Anaerobic biodegradation, however, can also be significant in some cases. For example, DDT degrades more rapidly under anaerobic conditions than under aerobic conditions.

- Microbial adaptation or acclimation. Biodegradation depends on the presence in the soil of organisms capable of metabolizing the waste constituents. The large and varied population of microorganisms in soil is likely to have some potential for favorable growth using organic wastes and constituents as nutrients. However, active metabolism usually requires a period of adaptation or acclimation that can range from several hours to several weeks or months, depending on the constituent or waste properties and the microorganisms involved.

- The availability of contaminants to micro-organisms. Releases that occur below the upper 6 to 8 inches of soil are less likely to be affected since relatively few organisms exist there. In addition, compounds with greater aqueous solubilities are generally more available for degradation. However, high solubility also correlates directly to the degree of mobility. If relatively permeable soil conditions prevail and constituents migrate rapidly, they are less likely to be retained long enough in the soil for biodegradation to occur.

- Other factors. Activity of organisms is also dependent on favorable temperature and pH conditions as well as the availability of other organic and inorganic nutrients for metabolism.

Rates of Hydrolysis, Photolysis, and Oxidation--Chemical and physical transformation of the waste can also affect the identity, amounts, and transport behavior of the waste constituents. Photolysis is important primarily for chemicals on the land surface, whereas hydrolysis and oxidation can occur at various depths.

Published literature sources should be consulted to determine whether individual constituents are likely to degraded by these processes, but it should be recognized that most literature values refer to aqueous systems. Relevant references include Elliott and Stevenson, 1977; Sims et al, 1984; and U.S. EPA, 1985. Chemical and physical degradation will also be affected by soil characteristics such as pH, water content, and soil type.

9.3.2 Unit Characterization

Unit-related factors that may be important in characterizing a release include:

- Unit design and operating characteristics;
- Release type (point-source or nonpoint-source);
- Depth of the release;
- Magnitude of the release; and
- Timing of the release.

9.3.2.1 Unit Design and Operating Characteristics

Information on design and operating characteristics of a unit can be helpful in characterizing a release. Table 9-5 presents important mechanisms of contaminant release to soils for various unit types. This information can be used to identify areas for initial soil monitoring.

9.3.2.2 Release Type (Point or Non-Point Source)

The owner or operator should establish whether the release involved a localized (point) source or a non-point source. Units that are likely sources of

TABLE 9-5
POTENTIAL RELEASE MECHANISMS FOR VARIOUS UNIT TYPES

Unit Type	Release Mechanisms
Surface Impoundment	Loading/unloading areas Releases from overtopping Seepage
Landfill	Migration of releases outside the unit's runoff collection and containment system Migration of releases outside the containment area from loading and unloading operations Leakage through dikes or unlined portions to surrounding soils
Waste Pile	Migration of runoff outside the unit's runoff collection and containment system Migration of releases outside the containment area from loading and unloading operations. Seepage through underlying soils
Land Treatment Unit	Migration of runoff outside the containment area Passage of leachate into the soil horizon
Container Storage Area	Migration of runoff outside the containment area Loading/unloading areas Leaking drums
Above-ground or In-ground Tank	Releases from overflow Leaks through tank shell Leakage from coupling/uncoupling operations Leakage from cracked or corroded tanks
Incinerator	Routine releases from waste handling/preparation activities Leakage due to mechanical failure
Class I and IV Injection Wells	Leakage from waste handling operations at the well head

* Waste transfer stations and waste recycling operations generally have mechanisms of release similar to tanks.

localized releases to soil include container handling and storage areas, tanks, waste piles, and bulk chemical transfer areas (e.g., loading docks, pipelines, and staging areas). Non-point sources may include airborne particulate contamination originating from a land treatment unit and widespread leachate seeps from a landfill. Land treatment can also result in widespread releases beyond the treatment zone if such units are not properly designed and operated; refer to EPA's Permit Guidance Manual on Hazardous Waste Land Treatment Demonstration, July, 1986 (NTIS PB86-229192) for additional information on determining contamination from land treatment units. This manual also discusses use of the RITZ model (Regulatory and Investigation Treatment Zone Model), which may be particularly useful for evaluating mobility and degradation within the treatment zone. This model is discussed in more detail in Section 9.4.4.2.

The primary characteristic of a localized release is generally a limited area of relatively high contaminant concentration surrounded by larger areas of relatively clean soil. Therefore, the release characterization should focus on determining the boundaries of the contaminated area to minimize the analysis of numerous uncontaminated samples. Where appropriate, a survey of the area with an organic vapor analyzer, surface geophysical instruments (see Appendix C), or other rapid screening techniques may aid in narrowing the area under investigation. Stained soil and stressed vegetation may provide additional indications of contamination. However, even if the extent of contamination appears to be obvious, it is the responsibility of the owner or operator to verify boundaries of the contamination by analysis of samples from outside of the contaminated area.

Non-point type releases to soil may also result from deposition of particulates in the air, such as from an incinerator. Such releases generally have a characteristic distribution with concentrations often decreasing logarithmically away from the source and generally having low variability within a small area. The highest contaminant concentrations tend to follow the prevailing wind directions (See also Section 12 on Air). Non-point releases occurring via other mechanisms (e.g., land treatment) may be distributed more evenly over the affected area. In these situations, a large area may need to be investigated in order to determine the extent of contamination. However, the relative lack of "hot spots" may allow the number of samples per unit area to be smaller than for a point source release.

9.3.2.3 Depth of the Release

The owner or operator should consider the original depth of the release to soil and the depth to which contamination may have migrated since the release. Often, releases occur at the soil surface as a result of spillage or leakage. Releases directly to the subsurface can occur from leaking underground tanks, buried pipelines, waste piles, impoundments, landfills, etc.

Differentiating between deep and shallow soil or surficial soil can be important in sampling and in determining potential impacts of contaminated soil. Different methods to characterize releases within deep and surficial soils may be used. For example, sampling of surficial soil may involve the use of hand-driven coring equipment, whereas deep-soil contamination usually requires the use of power-driven equipment (see Section 9.6 for more information). In addition, deep-soil and surficial-soil contamination may be evaluated differently in the health and environmental assessment process discussed in Section 8. Assessment of surficial-soil contamination will involve assessing risk from potential ingestion of the contaminated soil as well as assessing potential impacts to ground water. The assessment of deep-soil contamination may be limited to determining the potential for the soil to act as a continuing source of potential contamination to ground water in the uppermost aquifer.

For purposes of the RFI, surficial or shallow-zone soils may be defined as those comprising the upper 2 feet of earth, although specific sites may exhibit surficial soil extending to depths of up to 12 feet or more. Considerations for determining the depth of the shallow-soil zone may include:

- Meteorological conditions (e.g., precipitation, erosion due to high winds, evaporation of soil-pore gases);

- Potential for excessive surface runoff, especially if runoff would result in gully formation;

- Transpiration, particularly from the root zone, and effects on vegetation and animals, including livestock, that may feed on the vegetation; and

- Land use, including potential for excavation/construction, use of the soil for fill material, installation of utilities (e.g., sewer lines or electrical cables), and farming activities.

Deep-soil zones, for purposes of the RFI, may be defined as those extending from 2 feet below the land surface to the ground-water surface. If deep-soil contamination is already affecting ground water (through inter-media transport), at a specific site consideration should be given to evaluating the potential for such contamination to act as a continuing source of ground-water contamination.

The depth to which a release may migrate depends on many factors, including volume of waste released, amount of water infiltrating the soil, age of the release, and chemical and physical properties of the waste and soil (as addressed in the previous section). In a porous, homogeneous soil, contaminants tend to move directly downward within the unsaturated zone. Lateral movement generally occurs only through dispersion and diffusion. However, changes in soil structure or composition with depth (stratification), and the presence of zones of seasonally saturated soil, fractures, and other features may cause contaminants to spread horizontally for some distance before migrating downward. Careful examination of soil cores and accurate measurement of physical properties and moisture content of soil are therefore essential in estimating the potential for contaminant transport.

Transport of chemicals in the soil is largely caused by diffusion and mass flow. Diffusion results from random thermal motion of molecules. Mass flow, also known as convective flow, is transport by a flowing liquid or by a gaseous phase. Mass flow is typically downward (due to gravity); however, mass flow could also be upward due to capillary action (e.g., if significant evaporation occurs at the surface). Mass flow is a much faster transport mechanism than is diffusion (Morrill et al., 1985).

Other factors that can promote downward contaminant migration include turnover of soil by burrowing animals, freeze/thaw cycles, and plowing or other human activities. All factors that may affect the depth of contamination should be considered. The owner or operator should use available information to estimate the depth of contamination and should then conduct sampling at appropriate depths to confirm these estimates.

Approaches to monitoring releases to soil will differ substantially depending on the depth of contamination. For investigations of both surficial- and deep-soil contamination, a phased approach may be used. Initial characterization will often necessitate a judgmental approach in which sampling depths are chosen based on available information (e.g., topography, soil stratigraphy, and visual indication of a release). Information derived from this initial phase can then be used to refine estimates of contaminant distribution and transport. This information will serve as a basis for any subsequent monitoring that may be necessary.

Where the source or precise location of a suspected release has not been clearly identified, screening sampling (See Section 9.6) may be necessary. Subsurface contamination can be detected by using geophysical methods or organic vapor probes. Geophysical methods, for example, can help in locating buried drums. Organic vapor analysis can be useful in estimating the lateral extent of soil contamination, but delineating the vertical extent of contamination may necessitate an additional effort such as core sampling and analysis. Sampling approaches for locating and delineating subsurface contaminant sources include systematic and random grid sampling. These approaches are discussed in Section 3. Geophysical methods are discussed in Section 10 (Ground Water) and in Appendix C (Geophysical Techniques).

9.3.2.4 Magnitude of the Release

Information on the magnitude of the release can be estimated from site operating records, unit design features, and other sources. The quantity (mass) of waste released to soil and the rate of release can affect the geographical extent and nature of the contamination. Each soil type has a specific sorptive capacity to bind contaminants. If the sorptive capacity is exceeded, contaminants tend to migrate through the soil toward the ground water. Therefore, a " minor" release may be, at least temporarily, immobilized in shallow soils, whereas a "major" release is more likely to result in ground-water contamination. The physical processes of volatilization and dissolution in water are also affected by contaminant concentrations and should, therefore, be considered in assessing the potential for inter-media transport. Section 9.4.4.3 provides additional guidance on estimating the mobility of constituents within contaminated soils.

9.3.2.5 Timing of the Release

Time-related factors that should be considered in characterizing a release include:

- Age of the release;
- Duration of the release;
- Frequency of the release; and
- Season (time of year).

The length of time that has passed since a release occurred can affect the extent of contamination, the chemical composition of the contaminants present in soil, and the potential for inter-media transport. Recent releases tend to be more similar in composition to the parent waste material and may also be more concentrated within the original boundaries of the release. If a recent release occurred at the land surface, contaminant volatilization to air or dissolution in overland runoff may be important transport mechanisms. Older releases are more likely to have undergone extensive chemical or biological changes that altered their original composition and may have migrated a considerable distance from their original location. If the contaminants are relatively mobile in soil, transport to ground water may be a concern; whereas soil-bound contaminants may be more likely affected by surface transport, such as runoff or wind. These factors should be considered in the selection of monitoring constituents and sampling locations.

The duration and frequency of the release can affect the amounts of waste released to the soil and their distribution in the soil. For example, a release that consisted of a single episode, such as a ruptured tank, may move as a discrete "slug" of contamination through the soil. On the other hand, intermittent or continuous releases may present a situation in which contaminants exist at different distances from the source and/or have undergone considerable chemical and biological decomposition. Therefore, the design of monitoring procedures and estimations of contaminant fate and transport should consider release duration and frequency.

The time of year or season may also affect release fate and transport. Volatile constituents are more likely to be released to the air or to migrate as subsurface gas during the warmer summer months. During the colder winter months, releases may be less mobile, especially if freezing occurs.

9.3.3 Characterization of the Environmental Setting

The nature and extent of contamination is affected by environmental processes such as dispersion and degradation acting after the release has occurred. Factors which should be considered include soil physical and chemical properties, subsurface geology and hydrology, and climatic or meteorologic patterns. These factors are discussed below.

Characteristics of the soil medium which should be considered in order to obtain representative samples for chemical or physical analysis include:

- The potentially large spatial variability of soil properties and contaminant distribution;
- Spatial and temporal fluctuations in soil moisture content; and
- The presence of solid, liquid, and gaseous phases in the unsaturated zone.

9.3.3.1 Spatial Variability

Spatial variability, or heterogeneity, can be defined as horizontal and vertical differences in soil properties occurring within the scale of the area under consideration. Vertical discontinuities are found in most soil profiles as a result of climatic changes during soil formation, alterations in topography or vegetative cover, etc. Soil layers show wide differences in their tendency to sorb contaminants or to transmit contaminants in a liquid form; therefore, a monitoring program that fails to consider vertical stratification will likely result in an inaccurate assessment of contaminant distribution. Variability in soil properties may also occur in the horizontal plane as a result of factors such as drainage, slope, land use history, and plant cover.

Soil and site maps will aid in designing sampling procedures by identifying drainage patterns, areas of high or low surface permeability, and areas susceptible to wind erosion and contaminant volatilization. Maps of unconsolidated deposits may be prepared from existing soil core information, well drilling logs, or from previous geological studies. Alternately, the information can be obtained from new soil borings. Since soil coring can be a resource-intensive activity, it is generally more efficient to also obtain samples from these cores for preliminary chemical analyses and to conduct such activity concurrent with investigation of releases to other media (e.g., ground water).

The number of cores necessary to characterize site soils depends on the site's geological complexity and size, the potential areal extent of the release, and the importance of defining small-scale discontinuities in surficial materials. Another consideration is the potential risk of spreading the contamination as a result of the sampling effort. For example, an improperly installed well casing could lead to leakage of contaminated water through formerly low permeability clay layer. The risks of disturbing the subsurface should be considered when determining the need for obtaining more data.

Chemical and physical measurements should be made for each distinct soil layer, or boundary between layers, that may be affected by a release. During drilling, the investigator should note on the drilling log the depths of soil horizons, soil types and textures, and the presence of cracks, channels, and zones containing plant roots or animal burrows. Soil variability, if apparent, should generally be accounted for by increasing the number of sample points for measurement of soil chemical and physical properties. Determination of the range and variability of values for soil properties and parameters will allow more accurate prediction of the mobility of contaminants in the soil.

9.3.3.2 Spatial and Temporal Fluctuations in Soil Moisture Content

As described earlier in this section, there are several mechanisms for transport of waste constituents in the soil. Release migration can be increased by the physical disturbance of the soil during freeze/thaw cycles or by burrowing animals. Movement can also be influenced by microbial-induced transformations. In addition, movement can occur through diffusion and mass flow of gases and liquids. Although all of these mechanisms exist, movement of hazardous waste or constituents through soil toward ground water occurs primarily by aqueous transport of dissolved chemicals in soil pore water. Soil moisture content affects the hydraulic conductivity of the soil and the transport of dissolved wastes through the unsaturated zone. Therefore, characterizing the storage and flow of water in the unsaturated zone is very important. Moisture in the unsaturated zone is in a dynamic state and is constantly acted upon by competing physical forces.

Water applied to the soil surface (primarily through precipitation) infiltrates downward under the influence of gravity until the soil moisture content reaches equilibrium with capillary forces. A zone of saturation (or wetting front) may occur beneath the bottom of a unit (e.g., an unlined lagoon) if the unit is providing a constant source of moisture. In a low porosity soil, such a saturation front may migrate downward through the unsaturated zone to the water table, and create a ground-water or liquid "mound" (see Figure 9-1). In a higher porosity soil, the saturation front may only extend a small distance below the unit, with liquid below this distance then moving through the soil under unsaturated conditions toward ground water (see Figure 9-1). In many cases, this area will remain partially saturated until the capillary fringe area is reached. The capillary fringe can be defined as the zone immediately above the water table where the pressure is less than atmospheric and where water and other liquids are held within the pore spaces against the force of gravity by interfacial forces (attractive forces between different molecules).

In certain cases, soil moisture characterization can also be affected by the presence of isolated zones of saturation and fluctuations in the depth to ground water, as illustrated in Figure 9-1. Where there is evidence of migration below the soil surface, these factors should be considered in the investigation by careful characterization of subsurface geology and measurement of hydraulic conductivity in each layer of soil that could be affected by subsurface contamination.

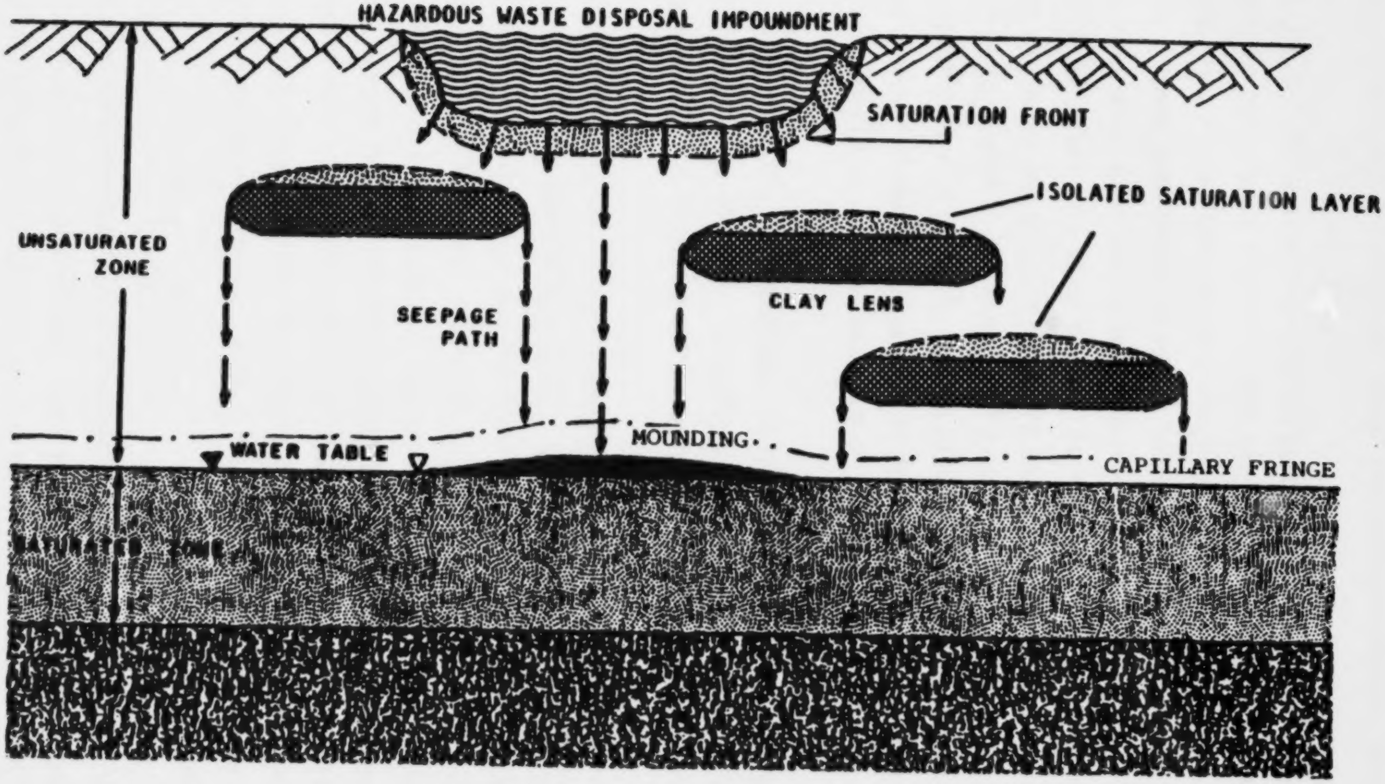
HAZARDOUS WASTE DISPOSAL IMPOUNDMENT
SATURATION FRONT
ISOLATED SATURATION LAYER
UNSATURATED ZONE
SEEPAGE PATH
CLAY LENS
MOUNDING
WATER TABLE
CAPILLARY FRINGE
SATURATED ZONE

Figure 9-1. Hydrogeologic conditions affecting soil moisture transport

9.3.3.3 Solid, Liquid, and Gaseous Materials in the Unsaturated Zone

Soil in the unsaturated zone generally contains solid, liquid, and gaseous phases. Depending upon the physical and chemical properties of the waste or its constituents, contaminants of concern may be bound to the soil, dissolved in the pore water, as a vapor within the soil pores or interstitial spaces, or as a distinct liquid phase. The investigation should therefore take into consideration the predominant form of the contaminant in the soil. For example, some whole-soil sampling methods may lead to losses of volatile chemicals, whereas analysis of soil-pore water may not be able to detect low solubility compounds such as PCBs that remain primarily adsorbed in the solid phase. Release characterization procedures should consider chemical and physical properties of both the soil and the waste constituents to assist in determining the nature and extent of contamination.

Soil classification--The owner or operator should classify each soil layer potentially affected by the release. One or more of the classification systems discussed below should be used, based on the objectives of the investigation.

- USDA Soil Classification system (USDA, 1975)--Primarily developed for agricultural purposes, the USDA system also provides information on typical soil profiles (e.g., 1-foot fine sandy loam over gravelly sand, depth to bedrock 12 feet), ranges of permeabilities for each layer, and approximate particle size ranges. These values are not generally accurate enough for predictive purposes, however, and should not be used to replace information collected on site. Existing information on regional soil types is available but suitable for initial planning purposes only. U.S. Department of Agriculture (USDA) county soil surveys may be obtained for most areas.

- Unified Soil Classification Systems (USCS) (Lambe and Whitman, 1979)-- A procedure for qualitative field classification of soils according to ASTM D2487-69, this system should be used to identify materials in soil boring logs. The USCS is based on field determination of the percentages of gravel, sand and fines in the soil, and on the plasticity and compressibility of fine-grained soils. Figure 9-2 displays the decision matrix used in classifying soils by this system.

Figure 9-2. Soil Terms

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UNIFIED SOIL CLASSIFICATION (USCS)

COARSE GRAINED SOILS

More than half of material is LARGER than No. 200 sieve size

FIELD IDENTIFICATION PROCEDURES (Excluding particles larger than 3" & basing fractions on estimated weights)			GROUP SYM-BOLS	TYPICAL NAMES
GRAVELS 50% (+) > 1/4" •	CLEAN GRAVELS Low % fines	Wide range in grain size and substantial amounts of all intermediate particle sizes	GW	Well graded gravels, gravel sand mixtures, little or no fines
		Predominantly one size or a range of sizes with some intermediate sizes missing	GP	Poorly graded gravels, gravel-sand mixtures, little or no fines
	GRAVELS W/FINES High % fines	Non-plastic fines (for identification procedures see ML)	GM	Silty gravels, poorly graded gravel-sand-silt mixtures
		Plastic fines (for identification procedures see CL)	GC	Clayey gravels, poorly graded gravel-sand-clay mixtures
SANDS 50% (+) ≤ 1/4" •	CLEAN SANDS Low % fines	Wide range in grain size and substantial amounts of all intermediate particle sizes	SW	Well graded sand, gravelly sands, little or no fines
		Predominantly one size or a range of sizes with some intermediate sizes missing	SP	Poorly graded sands, gravelly sands, little or no fines
	SANDS W/FINES High % fines	Non plastic fines (for identification procedures see ML)	SM	Silty sands, poorly graded sand-silt mixtures
		Plastic fines (for identification procedures see CL)	SC	Clayey sands, poorly graded sand-clay mixtures

FINE GRAINED SOILS

More than half of material is SMALLER than No. 200 sieve size

FIELD IDENTIFICATION PROCEDURES (Excluding particles larger than 3" & basing fractions on estimated weights)				GROUP SYM-BOLS	TYPICAL NAMES
Identification procedures on fraction smaller than No. 40 sieve size					
	DRY STRENGTH (Crushing Characteristics)	DILATANCY (Reaction to Shaking)	TOUGHNESS (Consistency Near Plastic Limit)		
SILTS & CLAYS Liquid limit < 50	None to slight	Quick to slow	None	ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity
	Medium to high	None to very slow	Medium	CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
	Slight to medium	Slow	Slight	OL	Organic silts and organic silt-clays of low plasticity
SILTS & CLAYS Liquid limit > 50	Slight to medium	Slow to none	Slight to medium	MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
	High to very high	None	High	CH	Inorganic clays of high plasticity, fat clays
	Medium to high	None to very slow	Slight to medium	OH	Organic clays of medium to high plasticity
HIGHLY ORGANIC SOILS	Readily identified by color, odor, spongy feel and frequently by fibrous texture			Pt	Peat and other organic soils

Boundary classifications-Soils possessing characteristics of two groups are designated by combining group symbols. For example GW-GC, well graded gravel-sand mixture with clay binder.
All sieve sizes on this chart are U.S. standard.

DENSITY OF GRANULAR SOILS

DESIGNATION	STANDARD PENETRATION RESISTANCE – BLOWS/FOOT
Very loose	0 - 4
Loose	5 - 10
Medium dense	11 - 30
Dense	31 - 50
Very dense	Over 50

CONSISTENCY OF COHESIVE SOILS

CONSISTENCY	UNC. COMPRESSIVE STR. TONS /SQ. FT.	STANDARD PENETRATION RESISTANCE – BLOWS/FOOT	FIELD IDENTIFICATION METHODS
Very soft	Less than 0.25	0 to 2	Easily penetrated several inches by fist
Soft	0.25 to 0.50	2 to 4	Easily penetrated several inches by thumb
Medium stiff	0.50 to 1.0	4 to 8	Can be penetrated several inches by thumb
Stiff	1.0 to 2.0	8 to 15	Readily indented by thumb
Very stiff	2.0 to 4.0	15 to 30	Readily indented by thumbnail
Hard	More than 4.0	Over 30	Indented with difficulty by thumbnail

ROCK TERMS

ROCK HARDNESS (FROM CORE SAMPLES)

DESCRIPTIVE TERMS	SCREWDRIVER OR KNIFE EFFECTS	HAMMER EFFECTS
Soft	Easily gouged	Crushes when pressed with hammer
Medium soft	Can be gouged	Breaks (one blow) Crumbly edges
Medium hard	Can be scratched	Breaks (one blow) Sharp edges
Hard	Cannot be scratched	Breaks conchoidally (several blows) Sharp edges

ROCK BROKENNESS

DESCRIPTIVE TERMS	ABBREVIATION	SPACING
Very broken	(V. Br.)	0 - 2"
Broken	(Br.)	2" - 1'
Blocky	(Bl.)	1' - 3'
Massive	(M.)	3' - 10'

LEGEND

SOIL SAMPLES - TYPES

S - 2" O.D. Split Barrel Sample
ST - 3" O.D. Undisturbed Sample
O - Other Samples, Specify in Remarks

ROCK SAMPLES - TYPES

X - NX (Conventional) Core (~ 2-1/8" O.D.)
Q - NQ (Wireline) Core (~ 1-7/8" O.D.)
Z - Other Core Sizes, Specify in Remarks

WATER LEVELS

12/18 ∇ 12.6' Initial Level w/Date & Depth
12/18 ▼ 12.6' Stabilized Level w/Date & Depth

The above classification systems are adequate for descriptive purposes and for qualitative estimates of the fluid transport properties of soil layers. Quantitative estimation of fluid transport properties of soil layers requires determination of the particle size distribution for each soil layer, as described below.

Particle size distribution--A measurement of particle size distribution should be made for each layer of soil potentially affected by the release. The recommended method for measurement of particle size distribution is a sieve/hydrometer analysis according to ASTM D422 (ASTM, 1984).

The particle size distribution has two major uses in a soils investigation: (1) estimation of the hydraulic conductivity of the soil by use of the Hazen (or similar) formula, and (2) assessment of soil sorptive capacity.

1. The hydraulic conductivity(K) may be estimated from the particle size distribution using the Hazen formula:

   $$K = A\,(d_{10})^2$$

   where d_{10} is equal to the effective grain size, which is that grain-size diameter at which 10 percent by weight of the particles are finer and 90 percent are coarser (Freeze and Cherry, 1979). The coefficient A is equal to 1.0 when K is in units of cm/sec and d_{10} is in mm. Results should be verified with in-situ hydraulic conductivity techniques.

2. Particle size can affect sorptive capacity and, therefore, the potential for retardation of contaminants in the soil. Sandy soils generally have a low sorptive capacity whereas clays generally have a high affinity for heavy metals and some organic contaminants. This is due in part to the fact that small clay particles have a larger surface area in relation to their volume than do larger sand particles. This larger surface area can result in stronger interactions with waste molecules. Clays may also bind contaminants due to the chemical structure of the clay matrix.

Porosity--Soil porosity is the percentage of the total soil volume not occupied by solid particles (i.e., the volume of the voids). In general, the greater the porosity, the more readily fluids may flow through the soil. An exception is clayey soils that tightly hold fluids by capillary forces. Porosity is usually measured by oven-drying an undisturbed sample and weighing it. It is then saturated with liquid and weighed again. Finally, the saturated sample is immersed in the same liquid, and the weight of the displaced liquid is measured. Porosity is the weight of liquid required to saturate the sample divided by the weight of liquid displaced, expressed as a decimal fraction.

Hydraulic conductivity--An essential physical property affecting contaminant mobility in soil is hydraulic conductivity. This property indicates the ease with which water at the prevailing viscosity will flow through the soil and is dependent on the porosity of the soil, grain size, degree of consolidation and cementation, and other soil factors.

Measurement of hydraulic conductivity in the saturated soil below the water table is fairly routine. Field and laboratory methods to determine saturated conductivity are discussed in the section on ground-water investigations (Section 10). Measurement of unsaturated conductivity is usually more difficult because the value changes with changing soil moisture content. Therefore, conductivities for a range of moisture contents may need to be determined for each type of soil at the facility.

Techniques for determining saturated hydraulic conductivity are provided in Method 9100 (Saturated Hydraulic Conductivity, Saturated Leachate Conductivity, and Intrinsic Permeability) from SW-846, Test Methods for Evaluating Solid Waste, EPA, 3rd edition, September, 1986. Methods 9100 includes techniques for:

- Laboratory
  - constant head methods; and
  - falling head methods.
- Field

- sample collection;
- well construction;
- well development;
- single well tests (slug tests); and
- references for multiple well (pumping tests).

A detailed discussion of field and laboratory methods for determining saturated and unsaturated hydraulic conductivity is also contained in Soil Properties Classification and Hydraulic Conductivity Testing (U.S. EPA, 1984). In general, field tests are recommended when the soil is heterogeneous, while laboratory tests may suffice for a soil without stratigraphic changes. Estimation of hydraulic conductivity from the particle size distribution may be used as a rough estimate for comparison purposes and if precise values are not needed.

Relative permeability--The hydraulic conductivity of a soil is usually established using water as the infiltrating liquid. However, at sites where there is the likelihood of a highly contaminated leachate or a separate liquid waste phase, the owner or operator should also consider determining conductivity with that liquid. The ratio of the permeability of a soil to a non-aqueous solution and its permeability to water is known as relative permeability.

The importance of determining this value is due to the potential effects of leachate on soil hydraulic properties. Changes in conductivity from infiltration of leachate may result from differences in the viscosity or surface tension of the waste, or the leachate may affect the soil structure so as to alter its permeability. For example, studies of waste migration through landfill liners made of clay have demonstrated that certain wastes may cause shrinking or expansion of the clay molecular structures, dissolve clays and organic matter, clog soil pores with fine particles, and cause other changes that affect permeability.

Soil sorptive capacity and Soil-Water Partition Coefficient (K_d)--The mobility of contaminants in soil depends not only on properties related to the physical structure of the soil, but also on the extent to which the soil material will retain, or adsorb, the hazardous constituents. The extent to which a constituent is adsorbed depends on chemical properties of the constituent and of the soil. Therefore, the sorptive capacity must be determined with reference to particular constituent and soil pairs.

The soil-water partition coefficient (K_d) is generally used to quantify soil sorption. K_d is the ratio of the adsorbed contaminant concentration to the dissolved concentration, at equilibrium.

There are two basic approaches to determining K_d: (1) soil adsorption laboratory tests, and (2) prediction from soil and constituent properties. The Soil Adsorption Isotherm (AI) test is widely used to estimate the extent of adsorption of a chemical (i.e., constituent) in soil systems. Adsorption is measured by equilibrating aqueous solutions containing varying concentrations of the test chemical with a known quantity of uncontaminated soil. After equilibrium is reached, the distribution of the chemical between the soil and water (K_d) is measured by a suitable analytical method.

The AI test has several desirable features. Adsorption results are highly reproducible. The test provides excellent quantitative data that are readily amenable to statistical analysis. In addition, it has relatively modest reagent, soils, laboratory space and equipment requirements. The ease of performing this test will depend on the physical/chemical properties of the contaminant and the availability of suitable analytical techniques to measure the chemical.

The AI test can be used to determine the soil adsorption potential of slightly water soluble to infinitely water soluble chemicals. In general, a chemical having a water solubility of less than 0.5 mg/l is not tested with this method because these chemicals are relatively immobile in soil. The U.S. EPA Office of Pesticides and Toxic Substances (U.S. EPA 1982a, 1982b) has compiled information on the use of the AI test, including a detailed discussion of apparatus, procedures, sources of error, statistical requirements, calculation methods, and limitations of the test.

A second approach for determining K_d is to estimate the value from soil and waste properties. Soil properties that should be considered when using this approach are particle size distribution cation exchange capacity, and soil organic carbon content. The waste properties that should be determined will vary depending on the type of waste. Lyman et al. (1981) discuss several methods for estimating K_d from chemical properties of the constituent (e.g., K_{ow} and water solubility) and the soil organic content. Data collection needs for waste properties were discussed earlier in this section.

Cation exchange capacity (CEC)--This parameter represents the extent to which the clay and humic fractions of the soil will retain charged species such as metal ions. The CEC is an important factor in evaluating transport of lead, cadmium, and other toxic metals. Soils with a high CEC will retain correspondingly high levels of these inorganics. Although hazardous constituents may be immobilized by such soils in the short-term, such conditions do not rule out the possibility of future releases given certain conditions (e.g., action of additional releases of low pH). A method for the determination of CEC is detailed in SW-846, Method 9081 (U.S. EPA, 1986c).

Organic carbon content--The amount of natural organic material in a soil can have a strong effect on retention of organic pollutants. The greater the fraction by weight of organic carbon (F_{oc}), the greater the adsorption of organics. Soil F_{oc} ranges from under 2 percent for many subsurface soils to over 20 percent for a peat soil. An estimate of F_{oc} should be made based on literature values for similar soils if site-specific information is not available.

Soil pH--Soil pH affects the mobility of potentially ionized organic and inorganic chemicals in the soil. Compounds in these groups include organic and inorganic acids and bases, and metals.

Depth to ground water --The thickness of the unsaturated zone may affect the attenuation capacity of the soil and the time taken for contaminants to migrate to ground water. If significant, seasonal fluctuations in ground-water elevations should be identified as well as elevation changes due to pumping or other factors (e.g., tidal influences).

Pore-water velocity--Pore water velocity affects the time of travel of contaminants in unsaturated soil to ground water. For steady state flow and a unit hydraulic gradient (i.e., moisture content does not change with depth), the pore-water velocity can be calculated by the following equation:

$$V = q/\theta$$

where: V = pore water velocity, cm/day

q = volumetric flux/unit area, cm/day
θ = volumetric water content, dimensionless

A simple approximation of volumetric flux (q) is to assume that it is equal to percolation at the site. Percolation can be estimated by performing a water balance as described below. This approach for calculating pore-water velocity is limited by simplifying assumptions; however, the method may be used to develop an initial estimate for time of travel of contaminants. More detailed methods, which account for unsteady flow and differences in moisture content are described in the following reference:

> U.S. EPA. 1986. Criteria for identifying Areas of Vulnerable Hydrogeology Under the Resource Conservation and Recovery Act. NTIS PB86-224953. Office of Solid Waste. Washington, D.C. 20460.

Percolation (volumetric flux per unit area)--Movement of contaminants from unsaturated soil to ground water occurs primarily via dissolution and transport with percolating soil water. It is important, therefore, to determine the volume of water passing through the soil. The percolation rate, or volumetric flux, must be determined in order to calculate pore water velocity through the unsaturated zone. The rate of percolation can be estimated from the water balance equation:

$$PER = P - ET - DR$$

where: PER = Percolation/recharge to ground water
P = Precipitation and irrigation
ET = Evapotranspiration
DR = Direct surface runoff

Annual averages for P, ET and DR should be obtained from existing local sources. Sources of information to estimate PER include:

- State or Regional water agencies;

- Federal water agencies (Geological Survey, Forest Service); and

- National Weather Service stations.

It is recommended that site-specific ET and DR data be used if possible, since local conditions can vary significantly from regional estimates. More information on percolation and ground-water recharge can be found in standard ground-water texts such as Freeze and Cherry, 1979. Information on evapotranspiration and direct surface runoff may be found in the following references:

> U.S. EPA. 1975. Use of the Water Balance Method for Predicting Leachate Generation from Solid Waste Disposal Sites. EPA/530/SW-168. Office of Solid Waste. Washington, D.C. 20460.
>
> U.S. Geological Survey. 1982. National Handbook of Recommended Methods for Water Data Acquisition.

Volumetric water content--The volumetric water content is the percent of total soil volume that is filled with water. It is equal to the amount of water lost from the soil upon drying to constant weight at 105°C, expressed as the volume of water/bulk volume of soil. This parameter affects the unsaturated hydraulic conductivity and is required for calculation of pore-water velocity. At saturation, the volumetric water content is equal to the porosity of the soil.

Additional soil conditions--Additional soil conditions that may require special consideration in investigating releases to soil are discussed below.

- In certain dense, cohesive soils, water may move primarily through narrow solution channels or fracture zones rather than by permeating the bulk of the soil. This condition can sometimes be recognized by dark-colored deposits indicating the fractures or by the tendency of soil cores to break apart at the discontinuity.

- Decomposed rock (e.g., transitional soils) may have a low primary porosity but a high secondary porosity due to relict joints or fractures or solution channels. Therefore, most flow may occur through these cracks and channels rather than through the soil pores. As a result, the rate of fluid flow is likely to be high, and the low surface area within the joint or fracture system generally results in a low sorptive capacity. Because field conditions are highly variable, the characterization of soil structure should be sufficiently detailed to identify such joints or fractures that may provide contaminant pathways.

- Certain clay soils known as vertisols, or expandable clays, may fracture into large blocks when dry. These cracks can be a direct route for ground-water contamination. Soil surveys should be consulted to determine whether these soils are present at the site. They occur in, but are not limited to, eastern Mississippi and central and southern Texas. Other clay soils may also develop desiccation cracks to a lesser degree. In these cases, it may be advisable to sample during both wet and dry seasons.

- Sampling saturated soils may be accomplished with the same drilling techniques used for unsaturated soil sampling. Particular care must be taken to prevent contamination between soil layers. Methods of telescoping smaller diameter casing downward through larger diameter, grouted casing are useful for minimizing cross-contamination between soil layers (See Section 9.6 for additional information on telescoping methods).

- Frequently, the choice of sampling technique is dictated by mechanical factors. Hard, rocky, or dense soils may prevent the use of manual tube samplers or augers. Power-driven auger drill rigs equipped with split-spoon samplers can penetrate most soils. Power augers can penetrate most unconsolidated materials, but will not drill through rock, for which an air-driven rotary drill is the recommended method. Loose sandy soils will fail to be retained in a tube sampler; therefore a sampler equipped with a retaining device should be used in such cases. Core sampling should generally be carried out under the supervision of an experienced driller, in order to avoid poor results or damaged equipment.

- Where unfavorable soil conditions interfere with a proposed sampling location, the sampling point may have to be moved to a nearby location.

In the event that such conditions are encountered, new locations should be chosen that are adequate to characterize the release.

9.3.4 Sources of Existing Information

Considerable information may already be available to assist in characterizing a release. Existing information should be reviewed to avoid duplication of previous efforts and to aid in scoping the RFI. Any existing information relating to releases from the unit and to hydrogeological, meteorological, and environmental factors that could influence the persistence, transport, or location of contaminants should be reviewed. This information may aid in:

- Delineating the boundaries of the sampling area;
- Choosing sampling and analytical techniques; and
- Identifying information needs for later phases of the investigation, if necessary.

Information may be obtained from readily available sources of geological and meteorological data, waste characteristics, and facility operating records. (See also Sections 2, 3, 7 and Appendix A).

9.3.4.1 Geological and Climatological Data

The Federal government and most state governments compile geological data, soil surveys, land use records, and climatological information. These sources should be consulted for local geology, soil types, historical precipitation, ground-water elevation records, and other useful data. Sources which may be consulted for soils data include the Soil Conservation Service (SCS), Agricultural Stabilization and Conservation Service (ASCS), the U.S. Geological Survey (USGS), state soils bureaus and agricultural extension services, university soil science departments, and private consultants. Additional sources of geologic information include geotechnical boring logs for foundation studies, well logs made during drilling of water supply wells, and previous hydrogeologic investigation monitoring wells. These logs should indicate the depth, thickness, and character of geologic materials, and the depth to the water table. Climate and weather information can be obtained from:

National Climatic Center
Department of Commerce
Federal Building
Asheville, North Carolina 28801
Tel: (704)258-2850

9.3.4.2 Facility Records and Site Investigations

The owner or operator should plan investigation activities by focusing on the conditions specified in the permit or enforcement order. Facility records, the facility's RCRA permit application, and any previous site reports (e.g., the RFA report) should also be examined for any other information on unit characteristics, wastes produced at the facility, and other factors relevant to releases to soil. Facility operating records should have data on wastes treated, stored, or disposed of at the facility. Wastes regulated under RCRA are identified by a waste code that may also aid in identifying constituents of concern (see 40 CFR Part 261). Wastes originating within the facility may be identified through analysis of process control records. Unit releases (e.g., losses from leaking tanks) can sometimes be estimated from storage records.

9.4 Design of a Monitoring Program to Characterize Releases

9.4.1 Objectives of the Monitoring Program

Monitoring procedures that specify locations, numbers, depths, and collection techniques for soil samples should be prepared by the owner or operator prior to each sampling effort. These procedures should provide the justification for the proposed samples, in terms of their expected contribution to the investigation. Examples of soil monitoring objectives include:

- Describing soil contamination in a drainage channel where a release is known to have occurred;

- Establishing a random or systematic grid sampling network to determine soil contamination concentrations in all zones of a large area affected by airborne deposition; and

- Filling in data gaps concerning the transport of waste constituents within a permeable soil layer.

In preparing soil monitoring procedures, the owner or operator should take into consideration those factors discussed in Sections 9.3.1 through 9.3.4 that apply to the facility. Also see Section 9.4.4.3 (Predicting Mobility of Hazardous Constituents in Soil).

As discussed previously, the release characterization may be conducted in phases. The objectives of the initial soil characterization are generally to verify suspected releases or to begin characterizing known releases. This characterization should use relevant soil physical and chemical measurements and other information as described earlier. In developing the approach, the owner or operator should determine the following:

- Constituents and indicator parameters to be monitored;

- Sampling methods;

- Approximate study and background areas;

- Sample locations (judgmental or systematic approach); and

- Number of samples to be collected.

Depending on the outcome of the initial characterization effort, the owner or operator may be required to obtain additional data to characterize the release. The findings of the initial phase will dictate the objectives of any later phases. Such subsequent phrases will generally involve the following:

- Expanding the number of sampling locations to a wider area and/or depth, or increasing sampling density where data are sparse;

- Institution of a grid sampling approach to further assess releases identified by judgmental sampling (see Section 3);
- Addition or deletion of specific monitoring constituent or indicator parameters; and
- Sampling in areas of interest based on previous sampling or model predictions to confirm the suspected extent of the release.

There is no specified or recommended number of phases to complete a soil investigation. The owner or operator should determine through consultation with the regulatory agency whether the collected data are sufficient to meet the objectives of the investigation.

9.4.2 Monitoring Constituents and Indicator Parameters

The owner or operator should propose hazardous constituents for monitoring based on the composition of wastes known to be present or released to soils at the site (see Sections 3 and 7 and Appendix B). Additional measurements may include nonhazardous chemicals that could serve as indicators of the presence of hazardous constituents or that could mobilize or otherwise affect the fate and transport of hazardous constituents. Chemical and physical properties of the soil that can be measured from soil samples should also be included in the list of parameters (see Section 9.3.3.3).

Justification of monitoring constituent selection may be provided through detailed facility records or waste analyses, as explained in Section 3. If such justification is inadequate, it may be necessary to perform a broader analytical program (See Section 3 and Appendix B).

After or during the selection of monitoring constituents, the owner or operator should review guidance on compound-specific requirements for sampling and sample preservation. The laboratory should use EPA protocols and analytical procedures when available, and accepted QA/QC practices. Guidance and specific references in these areas are provided in Sections 2, 3, 4, and 7.

9.4.3 Monitoring Schedule

Monitoring frequency and duration determinations should be based primarily on the type of release to the soil. A single episode or intermittent release, as with any release, would require monitoring until the nature and extent of contamination has been characterized. This may be accomplished with one or two sample sets in some cases. Longer-term releases will usually necessitate a greater duration of sampling. Soil pore liquid may require more frequent monitoring than in soil solids since changes occur faster in these fluids. Frequency may also be adjusted generally as sampling results become available. As with single episode releases, longer-term releases are monitored until the nature and extent of contamination has been adequately characterized.

9.4.4 Monitoring Locations

9.4.4.1 Determine Study and Background Areas

Determination of the area of interest will depend on the site layout, topography, the distribution of surface soils, soil stratigraphy, and information on the nature and source of the release. The size and type of unit may affect the area under consideration. For example, a landfill may only require monitoring of the surrounding soil whereas an inactive land treatment facility may require sampling over the entire unit surface and beyond.

High variability in the chemical composition of soils makes determination of background levels for the constituents of concern essential. This is particularly important for quantification of metals, since toxic metals may occur naturally in soil. Background areas not affected by any facility release should be selected based on their similarity to the study area in terms of soil type, drainage, and other physical factors. Background soil samples should be taken from areas that are not near a suspected source of contamination and from the same stratigraphic layer as the study samples, if possible. Selection and sampling of appropriate background areas may be important because verification of a release in a contaminated area may involve a comparison of study and background concentrations.

The owner or operator could increase efficiency in the initial characterization effort by using rapid-screening techniques or (e.g., HNu or OVA) indicator measurements to establish the extent of the study area. Subsurface soil contamination can sometimes be identified by geophysical techniques such as electromagnetic and resistivity techniques (See Section 10 and Appendix C). Indicator parameters can also be helpful in establishing the extent of the monitoring area. For example, Total Organic Halogen (TOX) or Total Organic Carbon (TOC) analysis may be used to detect total chlorinated solvents. Such parameters may be used to characterize the nature and extent of a release but should always be accompanied by specific constituent analyses.

It is generally recommended that a sampling grid be developed for the site. Gridding of the area to be sampled prior to the sampling effort will aid in determining appropriate sampling locations and in describing these locations. Refer to Section 3.6 for additional information on gridding of a study site.

9.4.4.2 Determine Location and Number of Samples

The owner or operator should propose monitoring locations and the number of samples to be collected and analyzed. Samples should be taken from the vicinity of all units identified in the conditions of the permit or order as suspected or known sources of soil contamination. The total number of samples necessary for the initial investigation will depend on the extent of prior information, the suspected extent and severity of the release, and the objectives of the characterization. However, the following general guidance should aid the owner or operator to sample efficiently.

- Sampling efficiency may be increased by use of a proportional sampling approach, which involves dividing the area of concern into zones, based on proximity to the release source and/or other factors. The number of samples taken in each zone should be proportional to the area of a zone.

- Use of composite samples may be able to allow detection of contamination over an area of concern with a smaller number of analyses. Compositing involves pooling and homogenization of multiple soil samples. The composite is then analyzed to give an average value for soil contamination in that area. However, as discussed in Sections 3 and

7, composites should have very limited application during the RFI and should always be accompanied by an appropriate number of individual grab samples. The following additional limitations on compositing should be observed:

- Compositing is most useful when large numbers of soil samples can be easily collected (e.g., for surficial contamination). In order to obtain the maximum information from deep soil coring, individual grab samples are preferred over composites.

- Compositing should not be used when analyzing soils for volatile organics because the constituents of interest may be lost during homogenization and sample handling.

- The owner or operator should employ appropriate procedures for the evaluation and reporting of monitoring data. These procedures can vary in a site-specific manner but should result in determinations of the nature, extent, and rate of migration of the release. Where the release is obvious and/or chemically simple, it may be possible to characterize it readily from a descriptive presentation of concentrations found. However, where contamination is less obvious or the release is chemically complex, a statistical inference approach may be proposed. The owner or opertor should plan initially to take a descriptive approach to data evaluation in order to broadly delineate the extent of contamination. Statistical comparisons of monitoring data among monitoring locations and over time may be appropriate if a descriptive approach does not provide a clear characterization of the release. Further guidance on use of statistical methods in soil investigations is provided in the following documents:

  Barth, D.S. and B.J. Mason. 1984. Soil Sampling Quality Assurance User's Guide. U.S. EPA 600/4-84-043. NTIS PB84-198621. Washington, D.C. 20460.

Mason, B.J. 1983. Preparation of a Soil Sampling Protocol: Techniques and Strategies. NTIS PB83-206979. U.S. EPA 600/4-83-020. Washington, D.C. 20460.

- Characterization of contaminant distribution with depth necessitates sampling of each distinct soil layer that might be affected by the release and from boundaries between soil layers. If the soil profile contains thick layers of homogeneous soil, samples should be taken at regular intervals (e.g., every 5 feet). In addition, samples should be taken where borings intersect fracture systems, at interfaces of zones of high and low permeability materials, or at other features that could affect waste transport. The owner or operator should consider measurement of soil physical and hydraulic properties in each distinct soil layer. The objective of such measurements in the initial release characterization effort is to identify properties that vary with depth. This approach may indicate the use of stratified sampling in any future sampling phases. Determination of soil properties will also aid in refining conceptual models of contaminant transport and can be input for mathematical models of soil transport.

Modeling--Prediction of contaminant fate and transport can range from a "conceptual" model of waste behavior in the soil to complex computer programs requiring extensive input of soil and water budget data. The primary uses of predictive modeling in soil investigations are to locate appropriate sampling locations using site-specific input data and to estimate the future rate, extent, and concentration of contaminant releases.

Modeling of waste transport in the unsaturated zone is often difficult due to the generally high spatial variability in soil physical and hydraulic properties. Therefore, modeling should not be used to replace actual measured values (e.g., when establishing the limits of waste leaching or diffusion in soil). However, if used with caution, models can act as useful tools to guide sampling efforts by directing sampling towards site areas identified as soil/water flowpaths (e.g., a permeable soil layer). The owner or operator should discuss the use of specific models with the regulatory agency prior to use.

Numerous models, including computer models, have been developed to calculate water flow and contaminant transport under saturated and unsaturated soil conditions. In using such models, site-specific data on soils and wastes should be used. Ground water (saturated flow) models are discussed in Section 10. A U.S. Nuclear Regulatory Commission Report (Oster, 1982) may be reviewed for information on the applicability of 55 unsaturated flow and transport models. Use of the RITZ Model (U.S. EPA. 1986. Permit Guidance on Hazardous Waste land Treatment Demonstration) may be particularly appropriate in certain situations. The RITZ model describes a soil column, 1 meter square, with a depth equal to the land treatment zone (usually 1.5 m). The soil column consists of a plow zone and lower treatment zone that are made up of four phases: soil grains, pore water, pore air, and pore oil. Mobilization of constituents within the soil is accounted for by dispersion, advection, and migration between phases. The constituent may also be degraded by biochemical processes represented in the model. Output from the model includes the concentration (C) of a constituent at the bottom of the treatment zone, and the time (T) required for a constituent to travel a distance equal to the treatment zone depth. Although the RITZ model was developed for evaluating the effectiveness of land treatment units, the model may be used for other applications, as appropriate (see above referenced document).

Computer models if proposed for use in the RFI should (1) be well-documented; (2) have been peer reviewed; and (3) have undergone extensive field testing. As indicated previously, model documentation (e.g., model theory, structure, use, and testing) should be provided to the regulatory agency for review prior to use. Access to the relevant data sets should also be available upon request. The regulatory agency may also recommend that a sensitivity analysis be performed and that the results of the analysis be submitted with the model results. In selecting a model, the owner or operator should consider its applicability, limitations, data requirements, and resource requirements.

9.4.4.3 Predicting Mobility of Hazardous Constituents in Soil

Predicting the mobility of hazardous constituents in soil may be necessary in an RFI. The prediction may then be used to determine the probable vertical or lateral extent of contamination, which can be used to identify potential sampling locations. Mobility predictions may also be used in determining potential inter-media transfers from the soil to ground or surface water. Finally, mobility predictions may provide information that can be used during the Corrective Measures Study to differentiate between contaminated soil that should be removed from the site and that which may remain at the site without adversely affecting human health or the environment. Predicting mobility of soil constituents may be particularly relevant, as indicated in Section 8, for determining whether deep-soil contamination, or in some cases surficial-soil contamination, can lead to ground-water contamination at a level above health and environmental criteria (if such an impact has not already occurred).

There is no universally applicable, straightforward method for predicting the mobility of all hazardous constituents within soils under all possible sets of environmental conditions. Nor is there a universally applicable method of estimating the impact of constituents originating in the unsaturated zone on ground-water quality. To avoid unneeded efforts, the first question the owner or operator should address is whether this task is necessary. For example, the characterization of ground-water quality (conducted following the guidance in Section 10) may provide information sufficient to describe the extent of the release and to determine that a Corrective Measures Study is necessary; this should be true where the contaminated soils are within the uppermost aquifer, or when the hazardous constituents are very mobile. The ground-water impact characterization may not, however, provide information on the future impact of contaminated soils on ground water.

This section presents some general approaches for predicting constituent mobility in both saturated and unsaturated soils; it also discusses how to estimate the impact on ground-water quality of the constituents leached from unsaturated soils. The limitations of these methods are also reviewed.

9.4.4.3.1 Constituent Mobility

There are several means of investigating mobility, including a descriptive approach (i.e., consideration of constituent and soil properties), the use of mathematical models, and the use of laboratory models or leaching tests. Leaching tests have the advantage of being the only approach that integrates soil and constituent properties in a single evaluation, providing a conservative (reasonable worst case) estimate of the concentration within leachate of waste constituents that may eventually impact ground water. Leaching test results, coupled with site-specific factors, (e.g., soil cation exchange capacity, ground-water pH, and depth to ground water), can be used to design monitoring programs, determine potential for inter-media impacts, and evaluate options for contaminated-soil corrective measures.

The descriptive approach and the use of mathematical models (such as the RITZ Model, discussed previously) may be appropriate in those cases where assumptions implicit in the use of leaching tests are not applicable. For example, leaching tests may be overpredictive of leachate concentrations where extensive channeling (e.g., because of root zones) through the contaminated zone is present; in this case, the contact time between the leaching fluid (e.g., infiltrating precipitation) and the soil as well as the surface area of the soil exposed to the fluid would be less than that simulated by the leaching test. Leaching tests may also not be applicable where low redox (reduction/oxidation) conditions are identified. Consideration of redox conditions is particularly relevant for inorganics.

Perhaps the most widely used of all leaching tests is the Extraction Procedure (EP), which is presently used under 40 CFR Part 261.24 to determine whether wastes pose a hazard because of their potential to leach toxic constituents, primarily heavy metals. However, EPA has proposed (51 FR 21648, June 13, 1986) to replace the EP with a new test known as the Toxicity Characteristic Leaching Procedure (TCLP), which is designed to estimate the concentrations of organic compounds (including volatile organics) and inorganic compounds in leachate. The TCLP was also proposed and has since been finalized for use in the land disposal restrictions rule (51 FR 40572, November 7, 1986).

The owner or operator may use either of these leaching tests to predict the mobility of soil constituents, depending on the nature of the waste constituents of concern, subject to the limitations explained in this section. The TCLP is the preferred procdure, however, if organic constituents are of concern, since the TCLP was designed to primarily apply to organics. Other leaching tests, or modifications of the EP or TCLP leaching tests, may be applied, as appropriate. For example, the EP and TCLP leaching tests use a dilute acetic acid leaching fluid. If the potential is low for acidic conditions , neutral water (or local water, such as rain water) may be used as the leaching fluid. Because leaching of cyanide-containing waste under acidic conditions may force the evolution of hydrogen cyanide (HCN), evaluation of cyanide-containing wastes should be done with neutral water. Additional modifications may be appropriate in some cases. The owner or operator should review the procedures and test methods described in Sections 8 and 9 and Appendix J of Petitions to Delist Hazardous Waste, 1986 (EPA/530-SW-85-003), as well as Test Methods for Evaluating Solid Wastes (EPA/SW-846, GPO No. 955-001-00000-1), to determine what method, if any, is appropriate for evaluating soil contaminant levels based on actual conditions at the site.

9.4.4.3.2 Estimating Impact on Ground-Water Quality

As indicated above, leaching tests provide a conservative (reasonable worst case) prediction or estimate of the concentration within leachate of constituents that may impact ground water. However, the owner or operator should evaluate these results along with constituent properties and site-specific factors. Important constituent properties to consider include:

- Nature (e.g., organic, inorganic, ionic);
- Solubility;
- Octanol/water partition coefficient (Kow);
- Organic carbon absorption coefficient (Koc);
- Volatility (e.g., Henry's law constant);
- Dissociation constants (pK); and
- Degradation potential (e.g., hydrolysis, biodegradation).

Site-specific environmental factors include:

- Depth to ground water;
- Cation exchange capacity;
- Soil pH and Eh;
- Clay content;
- Particle-size distribution;
- Hydraulic conductivity;
- Porosity;

- Permeability;
- Sorptive capacity;
- Soil-water partition coefficient (Kd);
- Organic carbon content (Foc);
- Pore water velocity;
- Percolation (volumetric flux per unit area);
- Volumetric water content;
- Ground-water pH and Eh;
- Specific conductance; and
- Ground-water ionic and non-ionic species.

Refer to Section 9.3.2.3 for specific information regarding these factors.

Both constituent and site-specific factors should be evaluated, together with leaching test concentrations, to arrive at predictions of the potential impacts to ground water. For example, if the depth to ground water is great enough, and the soil cation exchange capacity is high, the owner or operator may be able to predict that metal species would be adsorbed by the soil before the soil leachate reaches the ground water. Particular attention, in this example, would be needed to ensure that the cation exchange capacity of the soil could not be exceeded. The characteristics of the metal ions that are displaced from the exchange sites should also be considered.

As another example, the soil-water partition coefficient (Kd) is useful for describing chemical mobility in the subsurface environment, and is widely used in studies of ground-water contamination. For primarily aqueous solutions, the partitioning between the aqueous solution and the solid medium can be derived from thermodynamic principles (Freeze and Cherry, 1979).

More commonly, Kd is determined from batch experiments in which the contaminated solution and geologic material of interest are brought into contact. After a period of time has elapsed (e.g., 24-hours), the degree of partitioning of the contaminant between the solution and the geologic material is determined. The partition coefficient is then calculated using the following equation:

$$K_d = \frac{\text{mass of sorbed chemical/gram of solid}}{\text{mass of chemical/ml of solution}}$$

The relative mobility of attenuated constituents in ground water can then be estimated as follows (Mills, et al., 1985).

where

$$V_a = \frac{V_s}{1 + \frac{K_d b}{n}}$$

where

V_a = average linerar velocity of attenuated constituent along centerline of plume, ft/day
V_s = ground-water velocity, ft/day
b = soil bulk density, g/cm^3
n = effective porosity, dimensionless
K_d = soil-water partition coefficient (cm^3/g)

The relative mobility of selected constituents, based on typical partition coefficients, is shown in Table 9-6. It is important to note that Kd is a simplified measure of the relative affinity of a chemical for the solution and the soil. K_d is highly site-specific, varying as a function of pH, redox conditions, soil characteristics, and the availability of alternate solution phases (organic and inorganic liquids, or colloidal solids). The general effect of pH and organic matter content on partition coefficients for metals is shown in Figure 9-3.

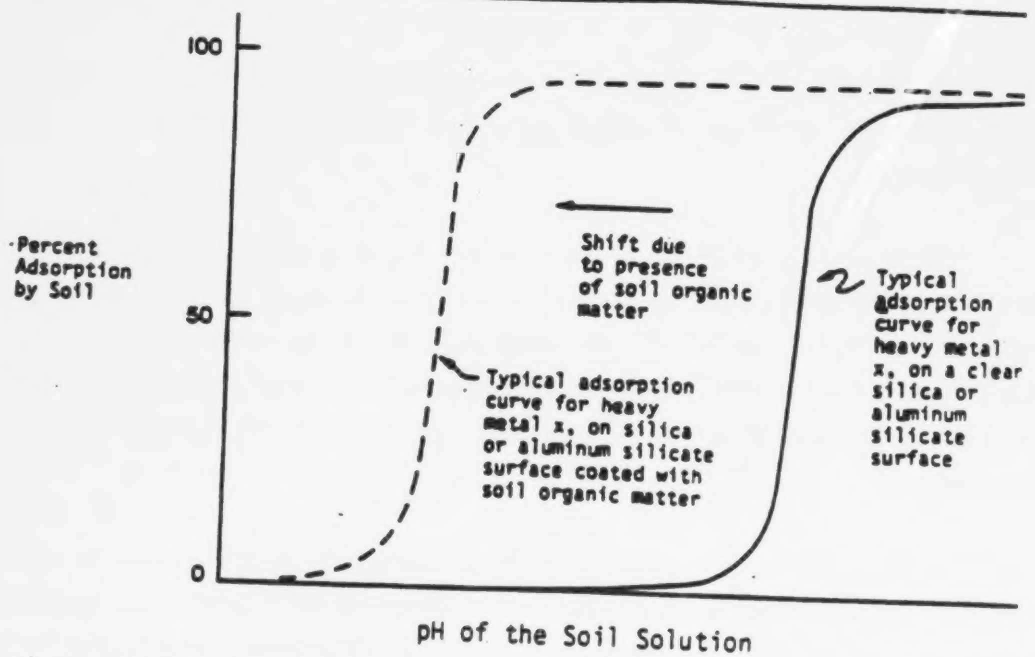
The K_d value selected for use in estimating chemical mobility should reflect the predominant chemical species in solution. One approach to estimating solution composition is to use thermodynamic stability diagrams, commonly illustrated as

TABLE 9-6 RELATIVE MOBILITY OF SOLUTES[1]

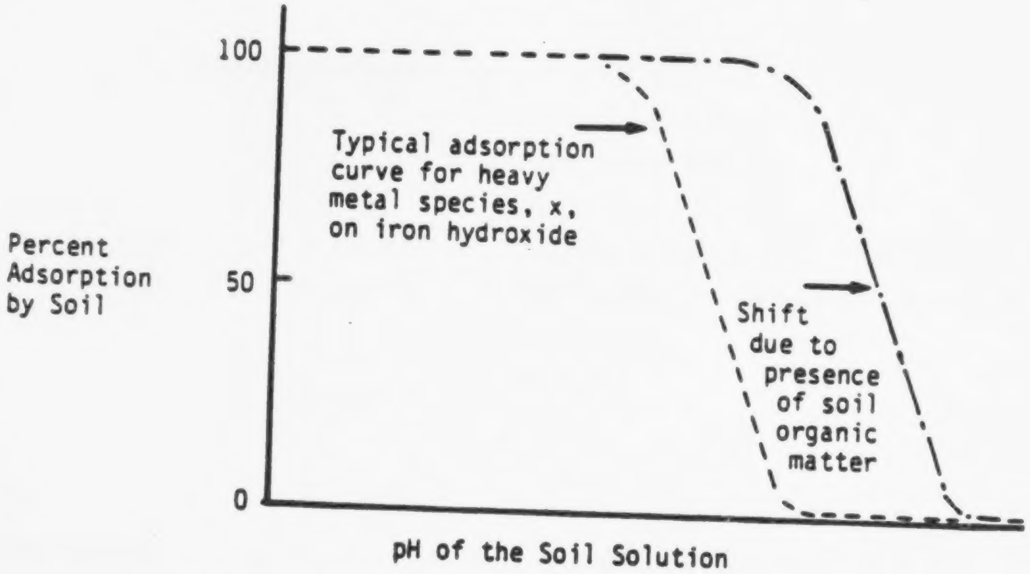
Group	Examples	Master Variables[2]
Conservative	Total Dissolved Solids	V
	Chloride	V
	Bromide	V
	Nitrate	V, Redox Conditions
	Sulfate	V, Redox Conditions
Slightly Attenuated	Boron Trichloroethylene	V pH, organic matter V , organic matter
Moderately Attenuated	Selenium Arsenic Benzene	V , pH, Iron hydroxides, V , pH, Iron hydroxides, V , organic matter
More Strongly Attenuated	Lead Mercury Pentachlorophenol	V , pH, Sulfate V , pH, Chloride V , organic matter

[1] Under typical ground-water conditions (i.e., neutral pH and oxidizing conditions). Under other conditions mobility may differ substantially. For example, acidic conditions can enhance the mobility of metals by several orders of magnitude.

[2] Variables which strongly influence the fate of the indicated solute groups. Based on data from Mills et al., 1985 and Rai and Zachara, 1984. (V = Average Linear Velocity)



a) Generalized Heavy Metal Adsorption Curve for Cationic Species (e.g., $CuOH^+$)



b) Generalized Heavy Metal Adsorption Curve for Anionic Species (e.g., CrO_4^{2-})

Figure 9-3. **Hypothetical Adsorption Curves for A) Cations and B) Anions Showing Effect of pH and Organic Matter (Mills et al., 1985)**

Eh-pH diagrams. These diagrams represent solution composition for specified chemicals as a function of redox potential (Eh) and of pH under equilibrium conditions.

Many metals of interest in ground-water contamination problems are influenced by redox conditions that result from changes in the oxidation state of the metal or from nonmetallic elements with which the metal can form complexes. Garrels and Christ (1965) present a comprehensive treatment of the subject and provide numerous Eh-pH diagrams that can be used for analysis of geological systems.

For any particular point in an Eh-pH diagram, a chemical reaction can be written that describes the equilibrium between the solid and dissolved phases of a particular constituent. The following equation represents the general form of the equilibrium reaction:

$$aA + bB = cC + dD$$

where:

a, b, c, d = number of moles of constituent
A and B = reactants
C and D = products

At equilibrium, the solubility constant (K) expresses the relation between the reactants and the products following the law of mass action:

$$K = \frac{[C]^c [D]^d}{[A]^a [B]^b}$$

The brackets signify an effective concentration, or activity, that is reported as molality (moles per liter). Solubility constants for many reactions in water are reported by Stumm and Morgan (1981). Alternatively, solubility constants can be calculated from thermodynamic data (Gibbs free energy) for products and reactants. Freeze and Cherry (1979) describe the use of thermodynamic data to calculate solubility constants for several constituents common in ground water.

An example illustrating the use of Eh-pH diagrams and the influence of redox conditions on solution composition is shown for mercury (Hg) in Figure 9-4. The stability diagram shown in Figure 9-4 is constructed for mercury-contaminated water that contains chloride (Cl) and dissolved sulfur species. The solid lines in the diagram represent the Eh-pH values at which the various phases are in equilibrium. For pH values of less than about 7 and Eh values greater than 0.5 volts (strong oxidizing conditions), $HgCl_2$ is the dominant dissolved species. For pH values greater than 7, and at a high redox potential, $Hg(OH)_2$ is the dominant dissolved species. The main equilibrium reaction in this Eh-pH environment is:

$$HgO + H_2O = Hg(OH)_2$$

From the law of mass action, the solubility relationship for this reaction is written as follows:

$$K = \frac{[Hg(OH)_2]}{[HgO][H_2O]}$$

At 25°C, the solubility constant (log K) for this reaction is -3.7 (Freeze and Cherry, 1979). The activity coefficients for a solid (HgO) and H_2O are assumed to be one; therefore, the concentration of $Hg(OH)_2$ in solution is calculated as follows:

$$[Hg(OH)_2] = K = 10^{-3.7} = 1.995 \times 10^{-4} \text{ moles/l} = 47 \text{ mg/l (mol. wgt} = 235 \text{ g/mole)}$$

The Eh-pH diagram can be used to estimate the concentration of mercury in solution at any particular point in the diagram if the solubility constant for the appropriate equilibrium reaction is known. For lower redox conditions (pH = 6.0, Eh = 0.0), the concentration of mercury in solution would be approximately 0.025 mg/l (Callahan et al., 1979).

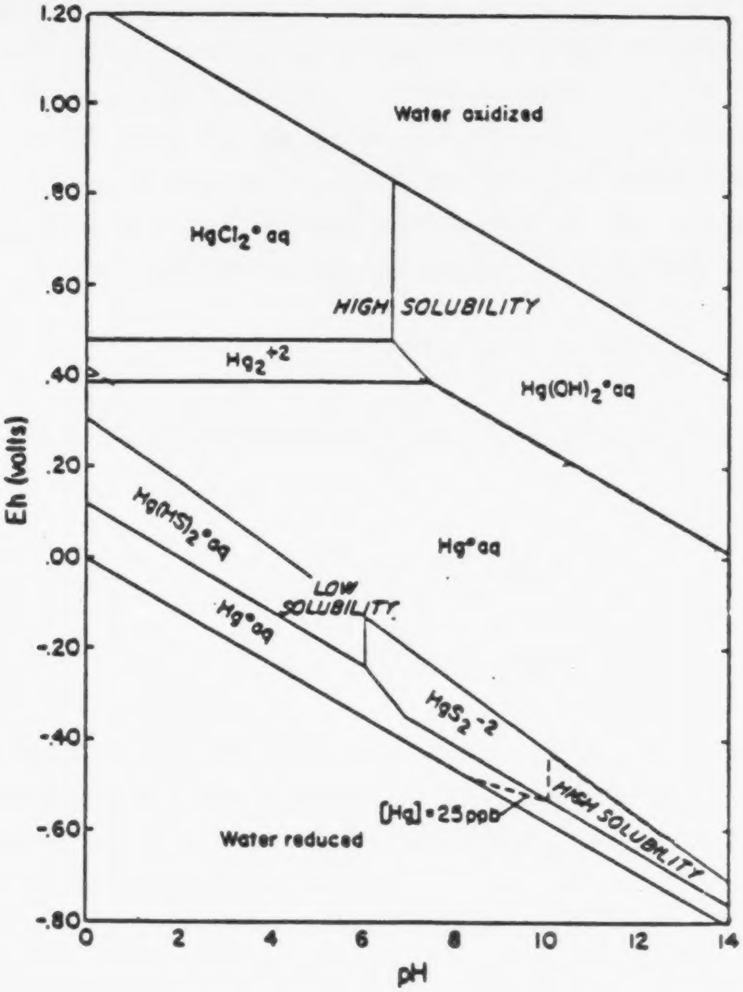


Figure 9-4. Fields of Stability for Aqueous Mercury at 25°C and Atmospheric Pressure (Callahan et al., 1979)

Several limitations are associated with the use of Eh-pH diagrams to predict dissolved chemical species, including the accuracy of thermodynamic data, the assumption of equilibrium conditions, and of other chemical processes such as adsorption that can maintain concentrations below those that would exist as a result of only solubility constraints. However, the Eh-pH diagrams serve to illustrate that solution composition depends on redox potential and that chemical mobility within a ground-water system may vary from one zone to another.

9.5 Data Presentation

The owner or operator will be required to report on the progress of the RFI at appropriate intervals during the investigation. The data should be reported in a clear and concise manner, with interpretations supported by the data. The following data presentation methods are suggested for soil investigations. Further information is provided in Section 5.

9.5.1 Waste and Unit Characterization

Waste and unit characteristics may be presented as:

- Tables of waste constituents and concentrations;
- Tables of relevant physical and chemical properties of waste and constituents;
- Narrative description of unit operations; and
- Surface map and plan drawings of the facility and waste unit(s).

9.5.2 Environmental Setting Characterization

Environmental characteristics may be presented as:

- A map and narrative description of soil classifications;
- Soil boring logs;

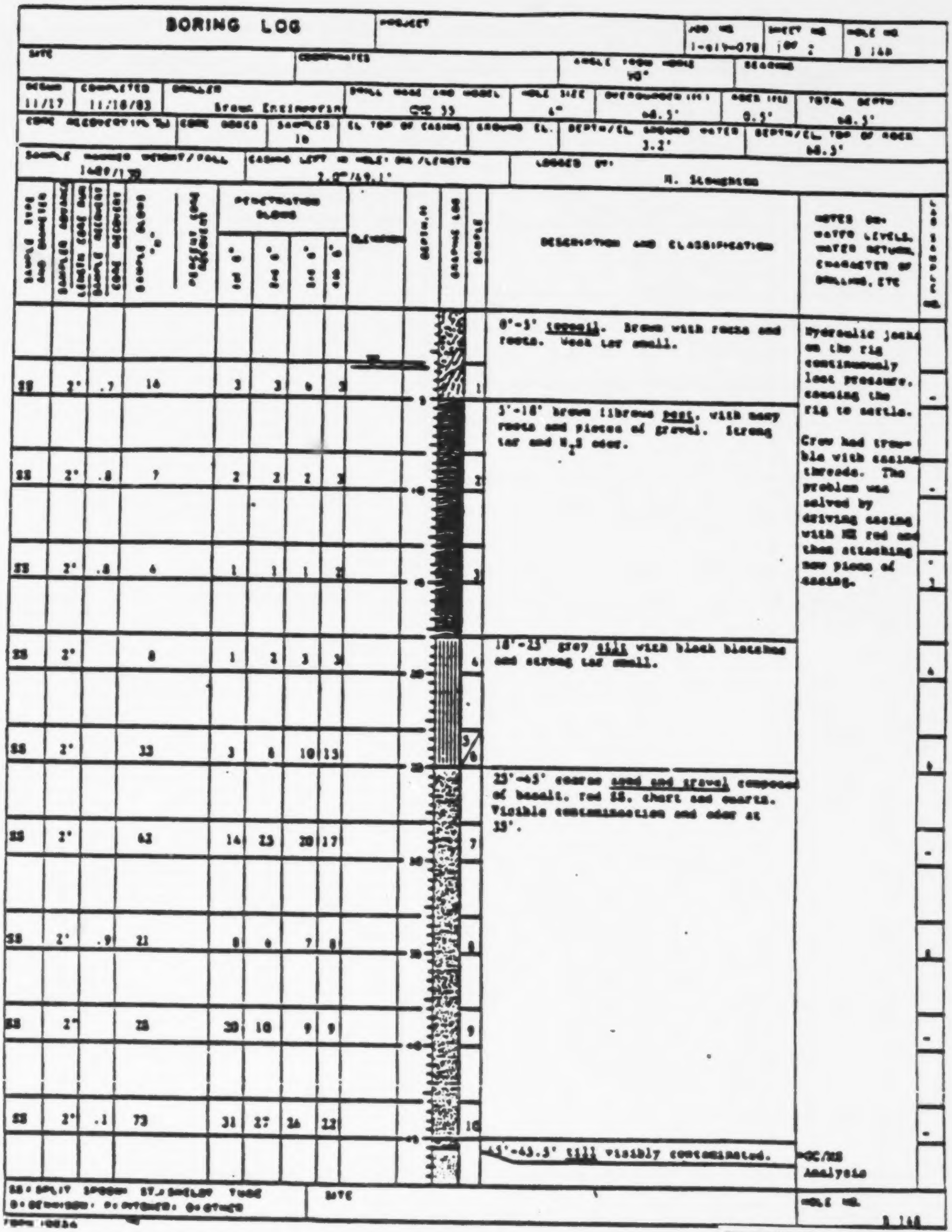
- Measurements of soil physical or hydrologic characteristics; and

- Onsite survey results (e.g., HNu/Photovac, geophysical techniques).

Soil and site map(s)--In addition to the required RCRA permit site topographic map, the owner or operator should prepare a map(s) displaying the location of surface soil types (described according to the appropriate classification system), paved areas, areas of artificially compacted soil, fill or other disturbed soil, and other features that could affect contaminant distribution. Specific guidance on the use of maps and other techniques such as aerial photographs and geophysical surveys is provided in Appendices A and C.

The owner or operator should develop maps of unconsolidated geologic materials at the site. These maps should identify the thicknesses, depths, and textures of soils, and the presence of saturated regions and other hydrogeological features. Subsurface soils should be identified according to accepted methods for description of soils (See Section 9.3.3.3). Figure 9-5 displays a typical soil boring log.

Graphical methods commonly used to display soil boring data are cross-sections, fence diagrams, and isopach maps. Cross-sections are typically derived from borings taken along a straight line through the site. Plotting the stratigraphy of surficial deposits against horizontal distance between sampling points gives a vertical profile or transect. Fence diagrams can depict the same type of information between points that are not in a straight line. An isopach map resembles a topographic map, however, the isopleth lines on an isopach map represent units of thickness of a particular soil layer rather than elevations. For example, a map of clay isopachs may be used to show the thickness in feet of a low permeability layer below a waste lagoon. Generally, to verify lateral continuity, more than one transect through a site will be necessary. When it is important to indicate the areal extent of a layer (e.g., where a clay lens is suspected to cause lateral transport in the unsaturated zone) both vertical and horizontal presentations may be necessary. Graphical methods are discussed in detail in Section 5 (Data Management and Presentation).



BORING LOG

PROJECT

JOB NO. 1-619-078

SHEET NO. 1 OF 2

HOLE NO. B 14B

SITE

COORDINATES

ANGLE FROM HORIZ. 90°

BEARING

BEGUN 11/17

COMPLETED 11/18/83

DRILLER Brown Engineering

DRILL MAKE AND MODEL CME 55

HOLE SIZE 6"

OVERBURDEN (FT) 48.5'

ROCK (FT) 0.5'

TOTAL DEPTH 48.5'

CORE RECOVERY (FT/%)

CORE BOXES

SAMPLES 10

EL. TOP OF CASING

GROUND EL.

DEPTH/EL. GROUND WATER 3.2'

DEPTH/EL. TOP OF ROCK 48.5'

SAMPLE HAMMER WEIGHT/FALL 140#/30"

CASING LEFT IN HOLE: DIA./LENGTH 2.0"/49.1'

LOGGED BY: H. Stoughton

SS	2"	.7	14	3	3	6	5	1
SS	2"	.8	7	2	2	2	3	2
SS	2"	.8	4	1	1	1	2	3
SS	2"		8	1	2	3	3	4
SS	2"		33	3	8	10	13	5/6
SS	2"		43	14	23	20	17	7
SS	2"	.9	21	8	6	7	8	8
SS	2"		28	20	10	9	9	9
SS	2"	.1	73	31	27	26	22	10

DESCRIPTION AND CLASSIFICATION

0'-3' topsoil. Brown with rocks and roots. Weak tar smell.

3'-18' brown fibrous peat, with many roots and pieces of gravel. Strong tar and H_2S odor.

18'-23' grey silt with black blotches and strong tar smell.

23'-45' coarse sand and gravel composed of basalt, red SS, chert and quartz. Visible contamination and odor at 35'.

45'-48.5' till visibly contaminated.

NOTES ON WATER LEVELS, WATER RETURN, CHARACTER OF DRILLING, ETC.

Hydraulic jacks on the rig continuously lost pressure, causing the rig to settle.

Crew had trouble with casing threads. The problem was solved by driving casing with NX rod and then attaching new piece of casing.

GC/MS Analysis

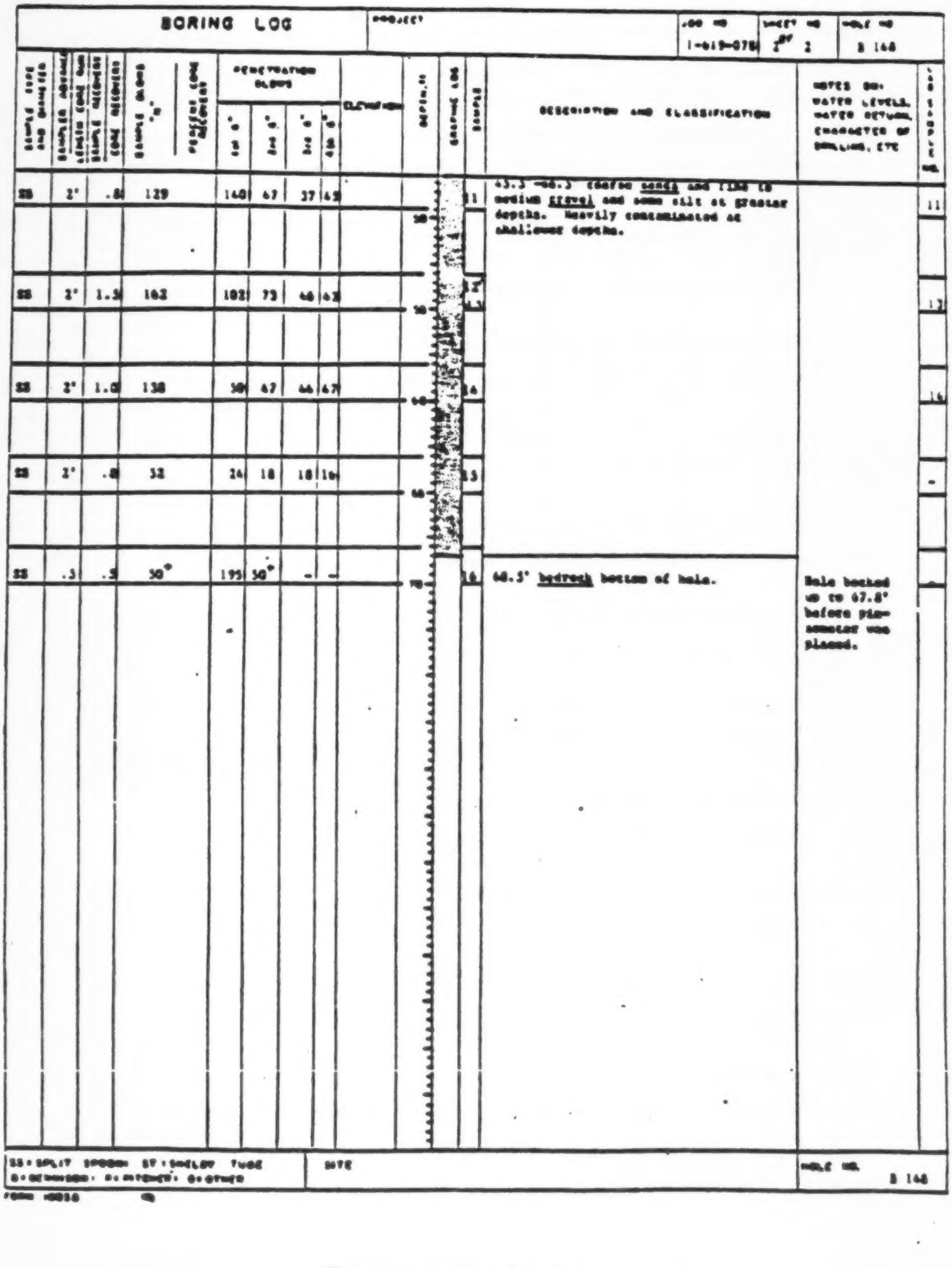
SS: SPLIT SPOON ST: SHELBY TUBE
D: DENISON P: PITCHER O: OTHER

DATE

HOLE NO. B 14B

Reproduced from best available copy.

Figure 9-5. Example of a completed boring log



BORING LOG

PROJECT

JOB NO	SHEET NO	HOLE NO
1-619-078	2 OF 2	B 148

[illegible]	[illegible]	[illegible]	[illegible]	PENETRATION BLOWS				ELEVATION	DEPTH, FT	GRAPHIC LOG	SAMPLE	DESCRIPTION AND CLASSIFICATION	NOTES ON: WATER LEVELS, WATER RETURN, CHARACTER OF DRILLING, ETC	LAB SAMPLE NO.
				1st 6"	2nd 6"	3rd 6"	4th 6"							
SS	2'	.8	129	140	67	37	65				11	43.5 -68.5' Coarse sand and fine to medium gravel and some silt at greater depths. Heavily contaminated at shallower depths.		11
									50					
SS	2'	1.3	162	102	73	46	43				12 13			13
									55					
SS	2'	1.0	138	50	47	44	47				14			14
									60					
SS	2'	.8	32	24	18	18	16				15			-
									65					
SS	.3	.5	50*	195	50*	-	-				16	68.5' bedrock bottom of hole.	Hole backed up to 67.8' before piezometer was placed.	-
									70					

SS: SPLIT SPOON ST: SHELBY TUBE
D: DENNISON P: PITCHER O: OTHER

DATE

HOLE NO. B 148

FORM [illegible]

Figure 9-5 (Continued)

9.5.3 Characterization of the Release

Graphical displays of contaminant distributions in soil may include:

- Area/site maps with concentrations indicated by numerical values, symbols, or isoconcentration lines;
- Three-dimensional isopleth plots of concentrations (including stack maps), such as are produced by computer graphics; and
- Vertical concentration contours (isopleths) plotted along a transect or fence diagram.

All graphical displays should be accompanied by data tables showing concentrations for each sampling location.

9.6 Field Methods

Both soil and soil pore water sampling may be utilized in the investigation. Chemical analysis of soil core samples may be used to characterize constituents of concern that are adsorbed to the solid matrix. Lysimeters can be installed in boreholes created during core sampling to identify mobile constituents that may migrate to ground water.

Appropriate sample collection and preservation techniques should be specified. When a soil sample is removed from its surroundings, chemical and physical changes can begin immediately. These changes include moisture loss, oxidation, gas exchange, loss of volatile components, increased or decreased biological activity, and potential contamination of the sample. Therefore, appropriate measures must be taken to store and preserve samples to minimize their degradation. Sampling techniques should not adversely affect analytical procedures and hence results. For example, use of fluids other than water during drilling can introduce organic or inorganic contaminants that may make quantification of the contaminants of concern impossible. The practice of coating metal parts of drilling equipment with oils or greases to prevent rust will have a similar effect.

Volatile compounds can sometimes be detected near the soil surface using rapid screening methods (e.g., portable photoionization detector such as HNu or Photovac or an organic vapor analyzer (OVA)). Organic vapors can also be detected and measured in shallow boreholes or in ground-water monitoring wells. Vapor sampling is especially useful for initial characterization because it is a rapid, semiquantitative technique. Benefits of rapid screening techniques include:

- The investigator can, in certain cases, quickly determine whether a sample is contaminated, thus, aiding in the identification of areas of concern;
- Samples that may undergo chemical changes with storage can be evaluated immediately; and
- These techniques can be used to investigate releases to several media simultaneously (e.g., subsurface gas, ground water and soil).

However, there are drawbacks to rapid screening techniques:

- They are not always indicative of all constituents that may be present in the release; and
- Detection limits may not be low enough to detect low level contamination, and additional analysis (e.g., GC/MS) may be required.

Soil sampling methods will vary with the depth of interest. For purposes of the RFI, these methods are described as "surficial" or "subsurface". Surficial sampling in the upper 20 cm of soil can usually be accomplished with a simple tools, including shovels, spatulas, soil punches, and ring samplers. Contaminants that have moved further downward in the soil profile often require tools such as tube samplers and augers. Manually operated tools are commonly useful to about 1 to 2 meters in depth, depending on the soil type. Below this depth, hydraulically or mechanically driven equipment is generally needed (See Everett et al, 1984 for additional information on soil sampling techniques, as well as Sections 3 and 7 of this Guidance for discussions of additional sampling methods and references).

Methods to sample soil pore water or other fluids are presented in Section 9.6.3.

9.6.1 Surficial Sampling Techniques

Surficial soils may also contain various materials, including rocks, vegetation, and man-made items. The owner or operator should propose how these materials will be treated (i.e., whether they will be discarded or analyzed separately). Care should be taken in choosing sampling equipment that will not adversely affect the analytical objectives (e.g., painted or chrome/nickel plated equipment may adversely affect metals analyses). Some commonly used surficial soil sampling techniques are discussed below.

9.6.1.1 Soil Punch

A soil punch is a thin-walled steel tube that is commonly 15 to 20 cm long and 1.3 cm to 5.1 cm in diameter. The tube is driven into the ground with a wooden mallet and twisted to free the sample. The punch is pulled out and the soil pushed or shaken from the tube. This technique is rapid but is generally not useful in rocky areas or in loose, granular soils that will not remain in the punch. Soil punching is not useful for soil structure descriptions because the method causes compaction that destroys natural fractures.

9.6.1.2 Ring Samplers

A ring sampler consists of a 15 to 30 cm diameter steel ring that is driven into the ground. The soil is subsequently removed for analysis. This technique is useful when results are to be expressed on a unit area basis, because the soil ring contains a known area of soil. Ring samplers will generally not be useful in loose, sandy soils or stiff clays.

9.6.1.3 Shovels, Spatulas, and Scoops

Collection of grab samples by shovel, spatula, or scoop is not recommended if sample area or volume determinations are required (the two previous methods are more accurate). The reproducibility of sample size is limited and subject to sample bias. The principal advantages of grab sampling are the efficiency of collection and the fact that samples may indicate the range of contaminant concentrations at the site.

9.6.1.4 Soil Probes (tube samplers)

Manual soil probes are designed to obtain samples from the upper two meters of the soil profile. The soil probe is commonly a stainless-steel or brass tube that is sharpened and beveled on one end and fitted with a T-handle. Soil probes are common agricultural tools and can be obtained in several diameters. The probe is pushed into the soil in 20 to 30 cm increments. At the desired depth, the tube is pulled out and the soil sample extruded. The sample may be considered "disturbed" or "undisturbed" depending on whether it can be removed intact. The samples, however, are generally considered to be disturbed for the purposes of engineering or physical measurements. Loose soils will be difficult to sample with this tool, and the borehole will tend to collapse when the tube is withdrawn to obtain samples.

9.6.1.5 Hand Augers

Augers have a spiral cutting blade that transports soil cuttings upwards. Hand-operated augers are generally used to a depth of approximately 6 feet. Single flight augers are pulled from the ground periodically and soil samples are taken from the threads of the auger. Continuous flight augers transport the loosened soil to the top of the borehole, where it can be collected. Augers provide highly disturbed samples. Limited information can be obtained on soil structure, bulk density, or permeability. Cross-contamination between soil layers is likely and depth information on various soil layers is not reliable. Therefore, reliance on augering as a sole sampling technique is not recommended. Augering may be used, however, in conjunction with tube sampling that obtains undisturbed samples.

9.6.2 Deep Sampling Methods

The subject of deep drilling is discussed more extensively in the section on ground-water sampling (see Section 10), since deep cores will generally be taken in conjunction with drilling for monitoring well emplacement. There are some techniques that are of particular importance to soil sampling and, therefore, a brief discussion is included here. Procedures for sampling with split-spoon and thin-wall tube corers and other equipment are presented in Section 7.

9.6.2.1 Hollow-Stem Augers

Hollow-stem augers have a continuous flight-cutting blade around a hollow metal cylinder. A stem with a plug is ordinarily kept inside the auger barrel to prevent soil from entering. When core samples are desired, the stem is withdrawn and a tube sampler may be inserted to the bottom of the borehole. This drilling method may be used for continuous soil sampling. An additional advantage of hollow-stem augers is that they do not require drilling fluids.

9.6.2.2 Solid-Stem Augers

Solid-stem augers, as the name implies, are augers that do not have an inner barrel. As with the manual variety, single-flight augers must be withdrawn each time a sample is desired, or samples may be taken from the cuttings brought to the surface by augers of the continuous flight type. Augers may be used in conjunction with tube samplers by withdrawing the auger and obtaining a sample from the bottom of the borehole. This sampling approach is only useful with soils that do not cave in or crumble after drilling.

9.6.2.3 Core Samplers

Soil coring devices that may be used with hydraulically or mechanically- driven drilling rigs include thin-walled Shelby tubes and split-spoon samplers. These are two of the most common samplers and are discussed below.

9.6.2.3.1 Thin-Walled Tube Samplers

The Shelby tube is a metal cylinder with the end sharpened and beveled for cutting into the soil. Common sizes used for field investigations are 1 to 3 inches in diameter. The tube is pushed down into the soil with a smooth even motion by applying downward pressure from a drilling rig or other apparatus. Thin-walled tubes produce high quality undisturbed cores that can be used for engineering and hydraulics testing but are useful only in cohesive soils as loose soils may fall out of the tube during removal. The soil must be extruded from the tube in a laboratory or in a field extruding unit because core removal is generally difficult. For rapid characterization of the soil stratigraphy in the field, split-spoon samplers are recommended.

9.6.2.3.2 Split-Spoon Samplers

A split-spoon consists of a hollow steel cylinder split in half and screwed into an "unsplit" outer tube and tip. This assembly can be connected to drill rods. The tube is commonly forced into the soil by applying a 140 pound sliding hammer, dropping 30 inches along the drill rod (ASTM, 1986). The number of hammer blows required to advance the sampler in six inch increments is recorded. The total blow count number for the second and third increments is related to a standard engineering parameter indicating soil density. After the tube is pulled from the soil, the cylinder is removed from the drill rod and opened, exposing the soil core. Core samples may be used to determine stratigraphy, for chemical and grain-size analysis, or for pore water extraction. Split-spoons are the preferred method for obtaining unconsolidated soil samples and may also be used to penetrate some types of rock.

9.6.2.4 Trenching

Trenches and test pits are useful where detailed examination of soil stratigraphy and geology is required. Trenching is generally limited for practicality to the top eight feet of soil. Shallow trenches may be dug manually, but in most instances, a backhoe will be faster and easier. Bulk soil samples may be obtained with this method.

9.6.3 Pore Water Sampling

When contaminants are suspected of migrating readily through the soil with infiltrating water, monitoring of water or other fluids in the unsaturated zone may be appropriate. Sampling soil pore water before it reaches the water table can provide an early warning of threats to ground water.

Compounds for which pore water sampling may be useful are those that are moderately to highly water soluble and thus are not appreciably retained on soil particles. Examples include poorly adsorbed inorganics such as cyanide or sulfate, halogenated solvents such as TCE, and organic acids. Due to the mobility of these compounds, pore water sampling will be most useful for current releases.

A common pore water collection technique uses a suction device called a pressure vacuum lysimeter, which consists of a porous ceramic cup connected by tubing to a collection flask and vacuum pump (Figure 9-6). The lysimeter cup may be permanently installed in a borehole of the appropriate depth, and if the hole is properly backfilled. Suction from the pump works against soil suction to pull water out of the silica flour surrounding the cup. This method will not work well in relatively dry soils.

An advantage of this method is that the installation is " permanent," allowing multiple samples from one spot to measure changes in pore water quality with time. Limitations include:

- Measurements cannot be correlated accurately with soil concentrations because the sample is obtained from an unknown volume of soil;
- Lysimeters are subject to plugging and are difficult to install in fractured or rocky soils;
- Some organic and inorganic constituents may be adsorbed by the ceramic cup (Teflon porous suction lysimeters may overcome this problem); and
- Volatile organics will be lost unless a special organics trap is installed in the system.

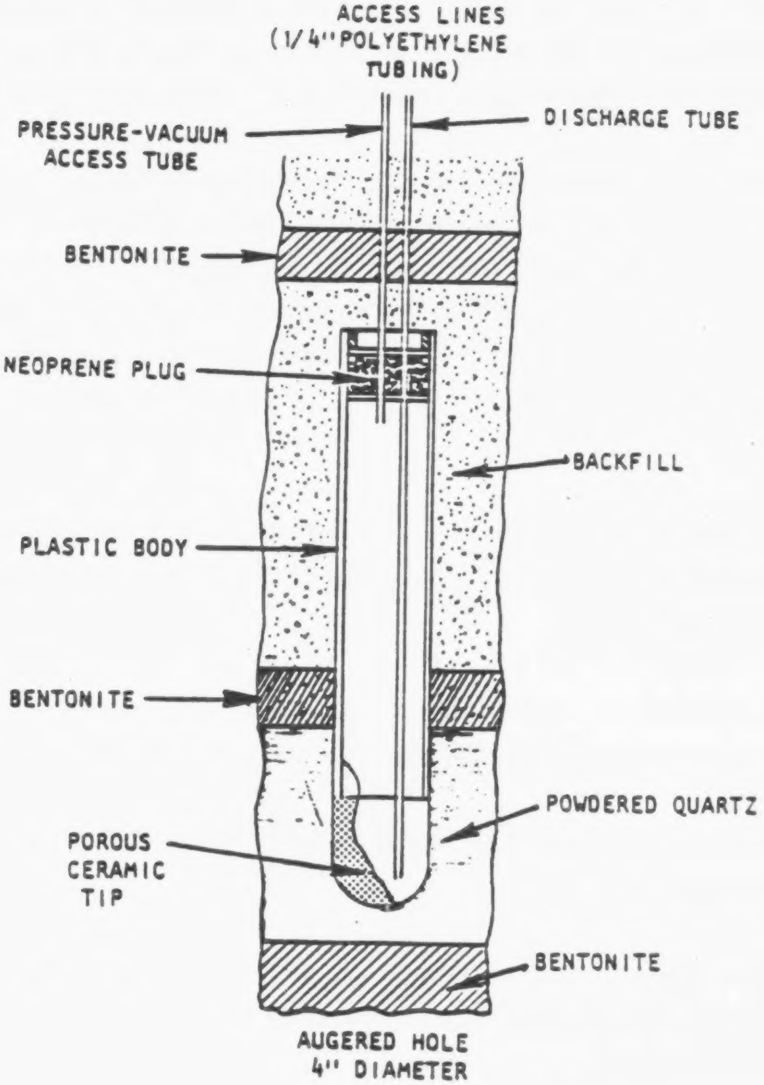

ACCESS LINES
(1/4" POLYETHYLENE TUBING)
PRESSURE-VACUUM ACCESS TUBE
DISCHARGE TUBE
BENTONITE
NEOPRENE PLUG
BACKFILL
PLASTIC BODY
BENTONITE
POWDERED QUARTZ
POROUS CERAMIC TIP
BENTONITE
AUGERED HOLE
4" DIAMETER

Figure 9-6. Typical Ceramic Cup Pressure/Vacuum Lysimeter

9.7 Checklist

RFI Checklist - Soils

Site Name/Location ____________________

Type of unit ____________________

1. Does waste characterization include the following information? (Y/N)

- Identity and composition of contaminants ____
- Physical state of contaminants ____
- Viscosity ____
- pH ____
- pka ____
- Density ____
- Water Solubility ____
- Henry's Law Constant ____
- k_{ow} ____
- Biodegradability ____
- Rates of hydrolysis, photolysis and oxidation ____

2. Does unit characterization include the following information? (Y/N)

- Age of unit ____
- Construction integrity ____
- Presence of liner (natural or synthetic) ____
- Location relative to ground-water table or bedrock or other confining barriers ____
- Unit operation data ____
- Presence of cover or other surface covering ____
- Presence of on/offsite buildings ____
- Depth and dimensions of unit ____
- Inspection records ____
- Operation logs ____
- Presence of natural or engineered barriers near unit ____

3. Does environmental setting information include the following information? (Y/N)

Site Soil Characteristics

- Surface soil distribution map ____
- Soil moisture content ____
- Predominant soil phase to sample (solid, liquid, gaseous) ____
- Soil classification ____
- Particle size distribution ____

RFI Checklist - Soils
(Continued)

- Porosity ____
- Hydraulic conductivity (saturated and unsaturated) ____
- Relative permeability ____
- Soil sorptive capacity ____
- Cation exchange capacity ____
- Organic carbon content ____
- Soil pH ____

Unsaturated Transport Characterization

- Depth to water table ____
- Pore water velocity ____
- Percolation ____
- Volumetric water content ____

4. Have the following data on the initial phase of the release characterization been collected? (Y/N)

- Geological and climatological data ____
- Facility records and site-specific investigations ____
- Area of contamination ____
- Distribution of contaminants within study area ____
- Depth of contamination ____
- Chemistry of contaminants ____
- Vertical rate of transport ____
- Lateral rate of transport in each stratum ____
- Persistence of contaminants in soil ____
- Potential for release from surface soils to air ____
- Potential for release from surface soils to surface water ____
- Existing soil/ground-water monitoring data ____
- Evidence of vegetative stress ____
- Potential for release to ground water ____
- Potential receptors ____

5. Have the following data on the subsequent phase(s) of the release characterization been collected? (Y/N)

- Further soil stratigraphic and hydrologic characterization data ____
- Expanded sampling data ____
- Geophysical data on plume location ____

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SECTION 10

GROUND WATER

10.1 Overview

The objective of an investigation of a release to ground water is to characterize the nature, extent, and rate of migration of a release of hazardous constituents to that medium. This section provides:

- A recommended strategy for characterizing releases to ground water, which includes characterization of the source and the environmental setting of the release, and conducting a monitoring program which will characterize the release itself;
- Recommendations for data organization and presentation;
- Appropriate field methods which may be used in the investigation; and
- A checklist of information that may be needed for release characterization.

The exact type and amount of information required for sufficient release characterization will be site-specific and should be determined through interactions between the regulatory agency and the facility owner or operator during the RFI process. This guidance does not define the specific data needed in all instances; however, it identifies possible information necessary to perform release characterizations and methods for obtaining this information. The RFI Checklist, presented at the end of this section, provides a tool for planning and tracking information for release characterization. This list is not meant as a list of requirements for all releases to ground water. Some release investigations will involve the collection of only a subset of the items listed, while others may involve the collection of additional data.

10.2 Approach for Characterizing Releases to Ground Water

10.2.1 General Approach

The owner or operator should develop a monitoring program to determine the nature, extent, and rate of migration of contaminant releases from SWMUs* to ground water. 3-Dimensional characterization may be particularly important. The initial monitoring phase should include a limited number of monitoring wells, located and screened in such a way that they are capable of providing background water quality and of intercepting any release. The regulatory agency will evaluate the adequacy of an existing monitoring system, if proposed for use in the initial monitoring phase. The owner or operator may be required to install new wells if the existing well system is found to be inadequate.

Initial ground-water sampling and analysis may be conducted for a limited set of monitoring constituents. This set should include a subset of the hazardous constituents of concern, and may also include indicator parameters (e.g., TOX). Guidance regarding the selection of monitoring constituents and indicator parameters is provided in Sections 3 and 7 and in Appendix B. Sampling frequency and duration should also be proposed in the RFI Work Plan.

Investigation of a suspected release may be terminated based on results from an initial monitoring phase if these results show that an actual release has not, in fact, occurred. If, however, contamination is found, the release must be adequately characterized through a subsequent monitoring phase(s).

Subsequent characterization involves determining the detailed chemical composition and the areal and vertical (i.e., three dimensional) extent of the contaminant release, as well as its rate of migration. This should be accomplished through direct sampling and analysis and, when appropriate, can be supplemented by indirect means such as geophysical methods (See Appendix C) and modeling techniques.

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* Guidance in this section applies to release from all solid waste management units, except releases to ground water from "regulated units" as defined under 40 CFR Part 264.90(a)(2). Releases to ground water from "regulated units" must be addressed according to the requirements of 40 CFR Parts 264.91 through 264.100 for purposes of detection, characterization and appropriate response.

Table 10-1 outlines a recommended strategy for characterizing release to ground water. Table 10-2 lists the specific tasks which may be used in implementing the strategy, and the corresponding data outputs. The steps delineated in these tables should generally be performed in sequential order, although some may be accomplished concurrently. For example, the site's hydrogeology may be investigated at the same time as waste and unit characterization; soil borings installed during hydrogeologic characterization may be converted into monitoring wells; and additional wells may be installed to more accurately characterize a release while a sampling and analysis program is in effect at existing wells.

The specific tasks to be conducted for each release will be determined on a site-specific basis. It should be noted that some of the characterization tasks may have been previously accomplished in conjunction with the 40 CFR Parts 264 and 265, Subpart F (ground-water monitoring) regulations.

As monitoring data become available, both within and at the conclusion of discrete investigation phases, it should be reported to the regulatory agency as directed. The regulatory agency will compare the monitoring data to applicable health and environmental criteria to determine the need for (1) interim corrective measures; and (2) a Corrective Measures Study. In addition, the regulatory agency will evaluate the monitoring data with respect to adequacy and completeness to determine the need for any additional monitoring efforts. The health and environmental criteria and a general discussion of how the regulatory agency will apply them are supplied in Section 8. A flow diagram illustrating is provided in Section 3 (See Figure 3-2).

Not withstanding the above process, the owner or operator has a continuing responsibility to identify and respond to emergency situations and to define priority situations that may warrant interim corrective measures. For these situations, the owner or operator is directed to obtain and follow the RCRA Contingency Plan under 40 CFR Part 264, Subpart D.

Case Study numbers 5, 6, 7 and 22 in Volume IV (Case Study Examples) illustrate the conduct of various aspects of ground-water investigations.

Table 10-1

Recommended Strategy For Characterizing Releases to Ground Water[1]

INITIAL PHASE

1. Collect and review preliminary information for use in formulating monitoring procedures:
    - Waste and unit information (including constituent identification and characterization)
    - Site hydrogeology and other environmental factors
    - Existing monitoring data
    - Regional flow net information
2. Identify and collect additional information necessary to characterize release:
    - Waste and unit information
    - Site hydrogeology and other environmental factors
    - Geophysical investigations (See Appendix C)
    - Conceptual model of release
    - Monitoring data
    - Inter-media transport
3. Develop monitoring procedures:
    - Select monitoring constituents and indicator parameters
    - Identify QA/QC and analytical procedures
    - Appropriate initial areal well locations (background and downgradient)
    - Collection of additional hydrogeologic data (if necessary)
    - Proper well screen interval selection
    - Borehole testing and use of test pitting
    - Sampling frequency and duration of monitoring
    - Identification of data presentation and evaluation procedures
4. Conduct initial monitoring phase:
    - Collect samples and complete field analyses
    - Analyze samples for selected parameters and constituents
5. Collect, evaluate and report results:
    - Compare monitoring results to health and environmental criteria and identify and respond to emergency situations and identify priority situations that warrant interim corrective measures - Notify regulatory agency
    - Determine completeness and adequacy of collected data
    - Summarize and present data in appropriate format
    - Determine if monitoring program objectives were met
    - Determine if monitoring locations, constituents and frequency were adequate to characterize release (nature, rate, and extent)

Table 10-1 (Continued)

Recommended Strategy For Characterizing Releases to Ground Water[1]

SUBSEQUENT PHASES (If Necessary)

1. Identify additional information necessary to characterize release:

   - Identify additional information needs
   - Perform further hydrogeologic characterization, if necessary
   - Add and delete constituents or indicator parameters as appropriate
   - Employ geophysical and other methods to estimate extent of release and to determine suitable new monitoring locations
   - Inter-media transport

2. Expand initial monitoring as necessary:

   - Expand density of monitoring locations
   - Expand monitoring locations to new areas
   - Install new monitoring wells

3. Conduct subsequent monitoring phases:

   - Collect samples and complete field analysis
   - Analyze samples for selected parameters and constituents

4. Collect, evaluate, and report results/identify additional information necessary to characterize release:

   - Compare monitoring results to health and environmental criteria and identify and respond to emergency situations and identify priority situations the warrant interim corrective measures - Notify regulatory agency
   - Determine completeness and adequacy of collected data
   - Summarize and present data in appropriate format
   - Determine if monitoring program objectives were met
   - Determine if monitoring locations, constitutents, and frequency were adequate to characterize release (nature, extent, and rate)
   - Identify additional information needs
   - Determine need to expand monitoring
   - Evaluate potential role of inter-media impact
   - Report results to regulatory agency

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[1] The possibility for intermedia transport of contamination exists, and should be anticipated throughout the investigation.

TABLE 10-2
RELEASE CHARACTERIZATION TASKS FOR GROUND WATER

Inventory Tasks	Investigatory Techniques	Data Presentation Formats/Out
1. Waste/Unit Characterization		
- Identify waste properties (e.g., pH, viscosity)	- Review existing information and conduct waste sampling if necessary (See Sections 3 & 7)	- Tabular presentation (See Section 5)
- Identify constituents of concern/possible indicator parameters	- Review existing information and conduct waste sampling if necessary (See Sections 3 & 7)	- Tabular presentation (See Section 5)
- Determine physical/chemical properties of constituents	- Review existing information (See Section 7)	- Tabular presentation (See Section 5)
- Determine unit dimensions and other important design features and operational conditions	- Review existing information and conduct unit examinations (See Section 7)	- Tabular presentations, facility maps & photographs & narrative discussion (See Section 5 and Appendix A)
- Investigate possible unit release mechanisms to help determine flow characteristics	- Review existing information and conduct unit examinations (See Section 7)	- Facility maps & photographs & narrative discussions (See Appendix A)
2. Environmental Setting Characterization		
- Examine surface features & topography for indications of subsurface conditions	- Review existing information facility maps, aerial & other photographs, site history/conduct surface geological surveys	- Facility map & photographs/text discussion (See Appendix A & C)
- Define subsurface conditions & materials, including soil and subsurface physical properties (e.g, porosity, cation exchange capacity)	- Review of existing geologic information	- Narrative discussions of geology
	- Soil borings and rock corings	- Boring and coring logs
	- Soil & subsurface material testing	- Subsurface profiles, tansects & fence diagrams (See Appendix A & Section 5)
	- Geophysical technqiues (See Appendix C)	- Tabular presentations of soil & subsurface physical & chemical properties
		- Geologic cross sections & geologic & soil maps (See Section 5 & 9 & Appendix A)
		- Structure contour maps (plar. view) of aquifer & aquitards (See Section 5 & Appendix A)

TABLE 10-2
RELEASE CHARACTERIZATION TASKS FOR GROUND WATER (continued)

Inventory Tasks	Investigatory Techniques	Data Presentation Formats/Outputs
2. Environmental Setting Characterization (Continued)		
- Identification of regional flow cells, ground-water flow paths & general hydrology, including hydraulic conductivities & aquifer interconnections	- Review of existing information - Installation of piezometers & water level measurements at different depths - Flow cell & flow net analyses using measured heads - Pumping & slug tests & trace studies - Geophysical techniques (See Appendix C)	- Narrative descriptions of ground-water conditions, flow cells, flow nets, flow patterns, including flow rates & direction - Water table or potentiometric maps (plan view) with flow lines (See Section 5) - hydrologic cross sectional maps (See Section 5) - Flow nets for vertical & horizontal flow - Tabular presentations of raw data & interpretive analysis
- Identification of potential receptors	- Review of existing information, area maps, etc.	- Narrative discussion & area maps
. Release Characterization		
- Determine background levels & determine vertical and horizontal extent of release, including concentrations of constituents & determine rate & directions of release migration	- Sampling & analysis of ground-water samples from monitoring system - Geophysical methods (See Appendix C) for detecting & tracking plume - Modeling to estimate extent of plume & rate & direction of plume migration	- Tabular presentations of constituent & indicator parameter analyses (See Section 5) - Iso-concentrations maps of contamination (See Section 5) - Maps of rates of release migration & direction showing locations of possible receptors (See Section 5) - Narrative discussion & interpretations of tabular & graphical presentations

10.2.2 Inter-media Transport

Indirect releases (inter-media transfer) to ground water may occur as a result of contaminant releases to soil and/or surface water that percolate or discharge to ground water. These releases may be recurrent or intermittent in nature, as in the case of overland run-off, and can vary considerably in areal extent. Direct releases to ground water may occur when waste materials are in direct contact with ground water (e.g., when a landfill rests below the water table).

Releases of contaminated ground water to other media may also occur, for example, in those cases where ground and surface waters are hydraulically connected. It is important for the owner or operator to be aware of the potential for such occurrences, and to communicate these to the regulatory agency when discovered.

This section provides guidance on characterizing ground-water releases from units, as well as those cases where inter-media transport has contaminated ground water. The owner or operator should be aware that releases to several media can often be investigated using concurrent techniques. For example, an organic vapor analyzer (OVA) may help to characterize the extent of soil and subsurface gas releases and, at the same time, be used to estimate the extent of a ground-water release.

10.3 Characterization of the Contaminant Source and the Environmental Setting

10.3.1 Waste Characterization

Knowledge of the waste constituents (historical and current) and their characteristics at the units of concern is essential in selecting monitoring constituents and well locations. Waste (source) information should include identifying volumes and concentrations of hazardous waste or constituents present, and their physical and chemical characteristics.

Identification of hazardous constituents may be a relatively simple matter of reviewing records of unit operations, but generally will require direct sampling and analysis of the waste in the unit. Hazardous constituents may be grouped by similar chemical and physical properties to aid in developing a more focused monitoring program. Knowledge of physical and chemical properties of hazardous constituents can help to determine their mobility, and their ability to degrade or persist in the environment. The mobility of chemicals in ground water is related to their solubility, volatility, sorption, partitioning, and density.

Section 3 provides additional guidance on monitoring constituent selection and Section 7 provides additional guidance on waste characterization. The following discussion describes several waste-related factors and properties which can aid in developing ground-water monitoring procedures:

- The mobility of a waste is highly influenced by its physical form. Solid and gaseous wastes are less likely to come in contact with ground water than liquid wastes, except in situations where the ground-water surface directly intersects the waste, or where infiltrating liquids are leaching through the unsaturated zone.

- The concentration of any constituent at the waste source may provide an indication of the concentration at which it may appear in the ground water.

- The chemical class (i.e., organic, inorganic, acid, base, etc.) provides an indication of how the waste might be detected in the ground water, and how the various components might react with the subsurface geologic materials, the ground water, and each other.

- The pH of a waste can provide an indication of the pH at which it would be expected to appear in the ground water. A low pH waste could also be expected to cause dissolution of some subsurface geologic materials (e.g., limestone), causing channelization and differential ground-water flow, as in karst areas.

- The acid dissociation constant of a chemical (pKa) is a value which indicates its equilibrium potential in water, and is equal to the pH at which the hydrogen ion is in equilibrium with its associated base. If direct pH measurements are not feasible, the concentration of a waste in combination with its pKa can be used to estimate the likely pH which will occur at equilibrium (in ground water), at a given temperature. Acid dissociation values can be found in most standard chemistry handbooks, and values for varying temperatures can be calculated using the Van't Hoff equation (Snoeyink and Jenkins, 1980).

- Viscosity is a measure of a liquid's resistance to flow at a given temperature. The more viscous a fluid is, the more resistant it is to flow. Highly viscous wastes may travel more slowly than the ground water, while low-viscosity wastes may travel more quickly than the ground water.

- Water solubility describes the mass of a compound that dissolves in or is miscible with water at a given temperature and pressure. Water solubility is important in assessing the fate and transport of the contaminants in ground water because it indicates the chemical's affinity for the aqueous medium. High water solubility permits greater amounts of the hazardous constituent to enter the aqueous phase, whereas low water solubility indicates that a contaminant can be present in ground water as a separate phase. Therefore, this parameter can be used to establish the potential for a constituent to enter and remain in the hydrologic cycle.

- The density of a substance (solid or liquid) is its weight per unit volume. The density of a waste will determine whether it sinks or floats when it encounters ground water, and will assist in locating well screen depths when attempting to monitor for specific hazardous constituents released to ground water.

- The log of the octanol/water partition coefficient (K_{ow}) is a measure of the relative affinity of a constituent for the neutral organic and inorganic phases represented by n-octanol and water, respectively. It is calculated from a ratio (P) of the equilibrium concentrations (C) of the constituent in each phase:

$$P = \frac{C_{octanol,}}{C_{water}} \text{ and } K_{ow} = \log P$$

The K_{ow} has been correlated to a number of factors for determining contaminant fate and transport. These include adsorption onto soil organic matter, bioaccumulation, and biological uptake. It also bears a relationship to aqueous solubility.

- The Henry's Law Constant of a constituent is the relative equilibrium ratio of a compound in air and water at a constant temperature. It can be estimated from the equilibrium vapor pressure divided by the solubility in water and has the units of atm-m^3/mole. The Henry's Law Constant expresses the equilibrium distribution of the constituent between air and water and indicates the relative ease with which the constituent may be removed from aqueous solution.

- Other influences of the waste constituents should also be considered. Constituents may react with soils, thereby altering the physical properties of the soil, most notably hydraulic conductivity. Chemical interactions among waste constituents should also be considered. Such interactions may affect mobility, reactivity, solubility, or toxicity of the constituents. The potential for wastes or reaction products to interact with unit construction materials (e.g., synthetic liners) should also be considered.

The references listed in Section 7 may be used to obtain information on the parameters discussed above. Other waste information may be found in facility records, permits, or permit applications. It should be noted that mixtures of chemicals may exhibit characteristics different than those of any single chemical.

10.3.2 Unit Characterization

Unsound unit design and operating practices can allow waste to migrate from a unit and possibly mix with natural runoff. Examples include surface impoundments with insufficient freeboard allowing for periodic overtopping; leaking tanks or containers; or land based units above shallow, low permeability materials which, if not properly designed and operated, can fill up with water and spill over. In addition, precipitation falling on exposed wastes can dissolve and thereby mobilize hazardous constituents. For example, at uncapped active or inactive waste piles and landfills, precipitation and leachate are likely to mix at the toe of the active face or the low point of the trench floor.

Unit dimensions (e.g., depth and surface area) and configuration (e.g., rectangular, parallel trenches), as well as volume (e.g., capacity) should also be described, since these factors will have a bearing on predicting the extent of the release and the development of a suitable monitoring network.

10.3.3 Characterization of the Environmental Setting

Hydrogeologic conditions at the site to be monitored should be evaluated for the potential impacts the setting may have on the development of a monitoring program and the quality of the resulting data. Several hydrogeologic parameters should be evaluated, including:

- Types and distribution of geologic materials;
- Occurrence and movement of ground water through these materials;
- Location of the facility with respect to the regional ground-water flow system;
- Relative permeability of the materials; and
- Potential interactions between contaminants and the geochemical parameters within the formation(s) of interest.

These conditions are interrelated and are therefore discussed collectively below.

There are three basic types of geologic materials through which ground water normally flows. These are: (1) porous media; (2) fractured media; and (3) fractured porous media. In porous media (e.g., sand and gravels, silt, loess, clay, till, and sandstone), ground water and contaminants move through the pore spaces between individual grains. In fractured media (e.g., dolomites, some shales, granites, and crystalline rocks), ground water and contaminants move through cracks or solution crevices in otherwise relatively impermeable rock. In fractured porous media (e.g., fractured tills, fractured sandstone, and some fractured shales), ground water and contaminants can move through both the intergranular pore spaces as well as cracks or crevices in the rock or soil. The occurrence and movement of ground water through pores and cracks or solution crevices depends on the relative effective porosity and degree of channeling occurring in cracks or crevices. Figure 10-1 illustrates the occurrence and movement of ground water and contaminants in the three types of geologic materials presented above.

The distribution of these three basic types of geologic materials is seldom homogeneous or uniform. In most settings, two or more types of materials will be present. Even for one type of material at a given site, large differences in hydrologic characteristics may be encountered. The heterogeneity of the materials can play a significant role in the rate of contaminant transport, as well as in developing appropriate monitoring procedures for a site.

Once the geologic setting is understood, the site hydrology should be valuated. The location of the site within the regional ground-water flow system, or regional flow net, should be determined to evaluate the potential for contaminant migration on the regional scale. Potentiometric surface data (water level information) for each applicable geologic formation at properly selected vertical and horizontal locations is needed to determine the horizontal and vertical ground-water flow paths (gradients) at the site. Figure 10-2(a) and (b) illustrate two geohydrologic settings commonly encountered in eastern regions of the United States, where ground water recharge exceeds evapotranspirational rates. Figure 10-2(c) illustrates a common geohydrologic setting for the arid western regions of the United States. The potential dimensions of a contaminant release would depend on a number of factors including ground-water recharge and discharge patterns, net precipitation, topography, surface water body locations, and the regional geologic setting.

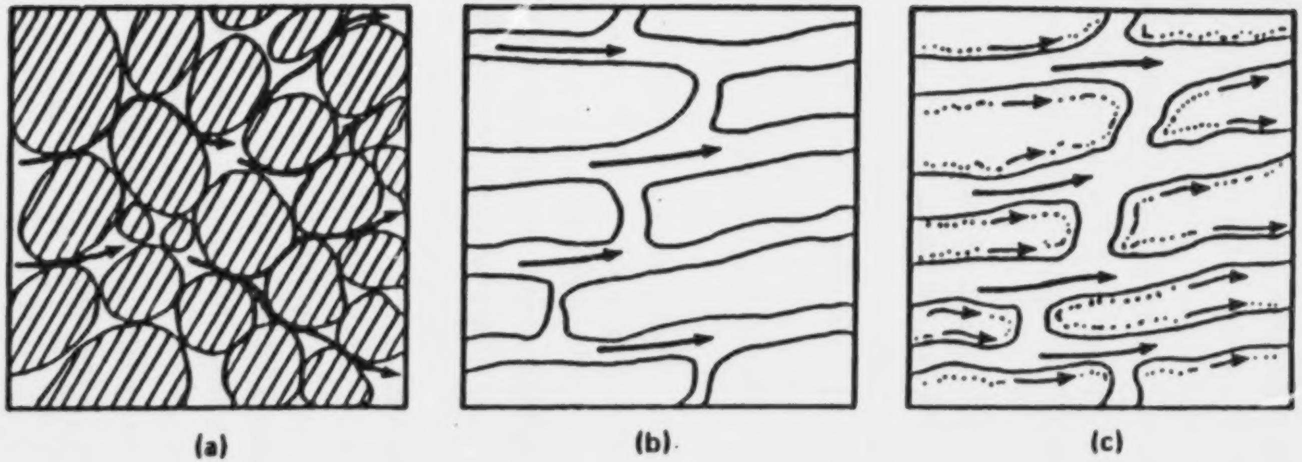
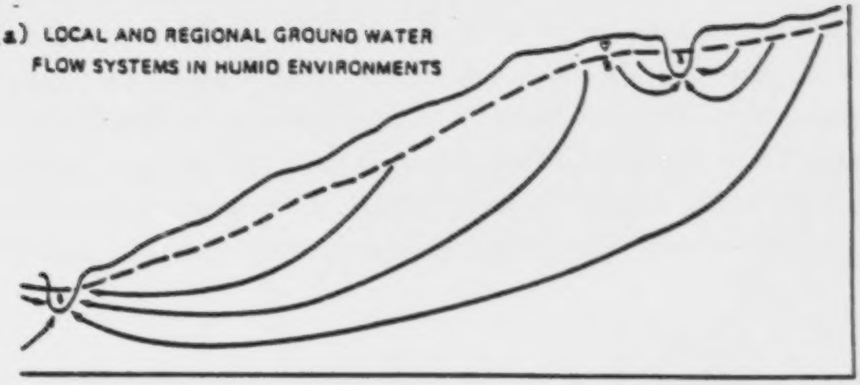
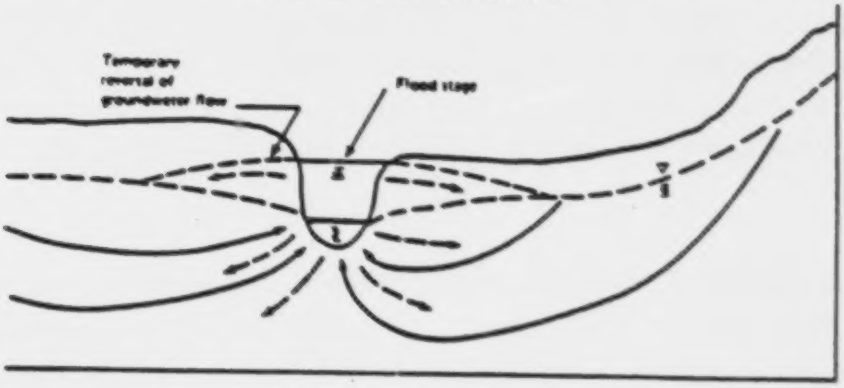


Figure 10-1. Occurrence and movement of ground water and contaminants through (a) porous media, (b) fractured or creviced media, (c) fractured porous media.

(a) LOCAL AND REGIONAL GROUND WATER FLOW SYSTEMS IN HUMID ENVIRONMENTS



(b) TEMPORARY REVERSAL OF GROUND-WATER FLOW DUE TO FLOODING OF A RIVER OR STREAM


Temporary
reversal of
groundwater flow
Flood stage

(c) TYPICAL GROUND-WATER FLOW PATHS IN ARID ENVIRONMENTS

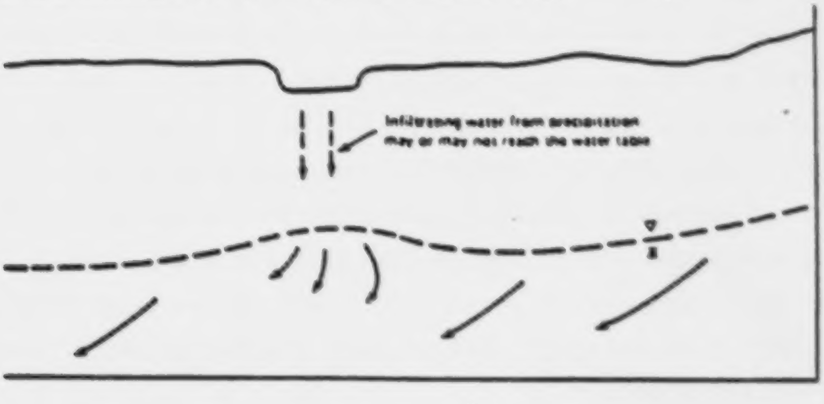

Infiltrating water from precipitation
may or may not reach the water table

Figure 10-2. Ground-water flow paths in some different hydrogeologic settings.

Table 10-3 and Figures 10-3 through 10-16 illustrate regional, intermediate, and local ground water regimes for the major ground-water regions in the United States. Generalized flow nets are shown superimposed on cross-sections of the geological units. Much of the information presented in the figures and following text descriptions were taken from Heath et. al., 1984 (Ground Water Regions of the U.S., U.S.G.S Water Supply Paper No. 2242). Following are descriptions of each of the major ground-water regions illustrated in the Figures (Figures 10-3 through 10-16).

Ground-water flow in the Western mountain Ranges region is influenced by melting snow and rainfall at higher altitudes. The thin soils and fractures in the underlying bedrock have a limited storage capacity and are quickly filled with recharging ground water flowing from higher elevations (See Figure 10-3). The remaining surface water runs overland to streams that may eventually recharge other areas. Streams that recharge gound water are referred to as 'losing streams." Figure 10-3 also shows local ground-water flow paths influenced by low permeability bedrock located in intermountain valleys throughout the mountain ranges.

The Alluvial Basins region consists of deep, unconsolidated sediments adjacent to mountain ranges. Precipitation runs rapidly off the mountains and infiltrates into the alluvium at the valley margins. The water moves through the sand and gravel layers toward the centers of the basins (Figure 10-4). The presence of disjointed masses of bedrock in this region is crucial to the hydrogeological regime. Low permeability igneous bedrock often isolates the ground water into individual basins with minimal exchange of ground water. Where the bedrock is composed of limestone or other highly permeable material, large regional flow systems encompassing many basins can develop. Recharge areas in this region are located in upland areas; lowland stream beds carry water only when sufficient runoff from the adjoining mountains occurs. Figure 10-4 also shows an example of a waste unit located in thick alluvium overlying a structurally complex uppermost aquifer. In this example, the localized structural geology exerts the most influence over the ground-water flow pattern.

TABLE 10-3. SUMMARY OF U.S GROUND WATER REGIONS

Region	Region Name (Heath, 1984)	Recharge Area	Discharge Area	Dimensions (miles)	Example
1	Western Mountain Ranges	infiltration in mountains and mountain fronts	streams and rivers	< 1-5 unconfined 5-60 confined	Wasatch Range, Utah
2	Alluvial Basins	plateau uplands	streams and rivers, some enclosed basins, localized springs and seeps in steeper terrain	< 1-20 unconfined 5-80 confined	Nevada
3	Columbia Lava Plateau	surface infiltration	rivers and streams	10-200 miles	Snake River Plain
4	Colorado Plateau	infiltration in plateau uplands; infiltration from surface waters	seeps, springs, and surface waters	5-80 miles	Southeast Utah
5	High Plains	surface infiltration	rivers and streams, seeps and springs along eastern escarpments	2-300 miles	Nebraska
6	Non-glaciated central	upland infiltration	springs, seeps, streams and rivers	< 1-40 miles	Ohio Great Miami
7	Glaciated Central	surface infiltration	springs, streams, rivers, and lakes	< 1-20 miles	Minnesota
8	Piedmont and Blue Ridge	surface infiltration	springs, seeps, and surface waters	< 1-5 miles	West Virginia
9	Northeast and Superior Uplands	upland infiltration	surface water	< 1-20 miles	Massachusetts
10	Atlantic & Gulf Coastal Plain	infiltration in outcrop areas	surface water or subsea leakage	10-150 miles	New Jersey
11	Southeast Coastal Plain	infiltration in outcrop areas	surface water or subsea leakage	1-80 miles	South Georgia
12	Hawaiian Islands	surface infiltration	springs, seeps, and surface waters	< 1-30 miles	Oahu, Hawaii
13	Alaska	variable*	variable*	variable*	North Slope

* The recharge area, discharge area, and dimensions of the flow cells within Alaska are highly variable due to the wide range in topography and geology found in this region.

WESTERN MOUNTAIN RANGES
(Mountains with thin soils over fractured rocks, alternating with narrow alluvial and, in part, glaciated valleys)

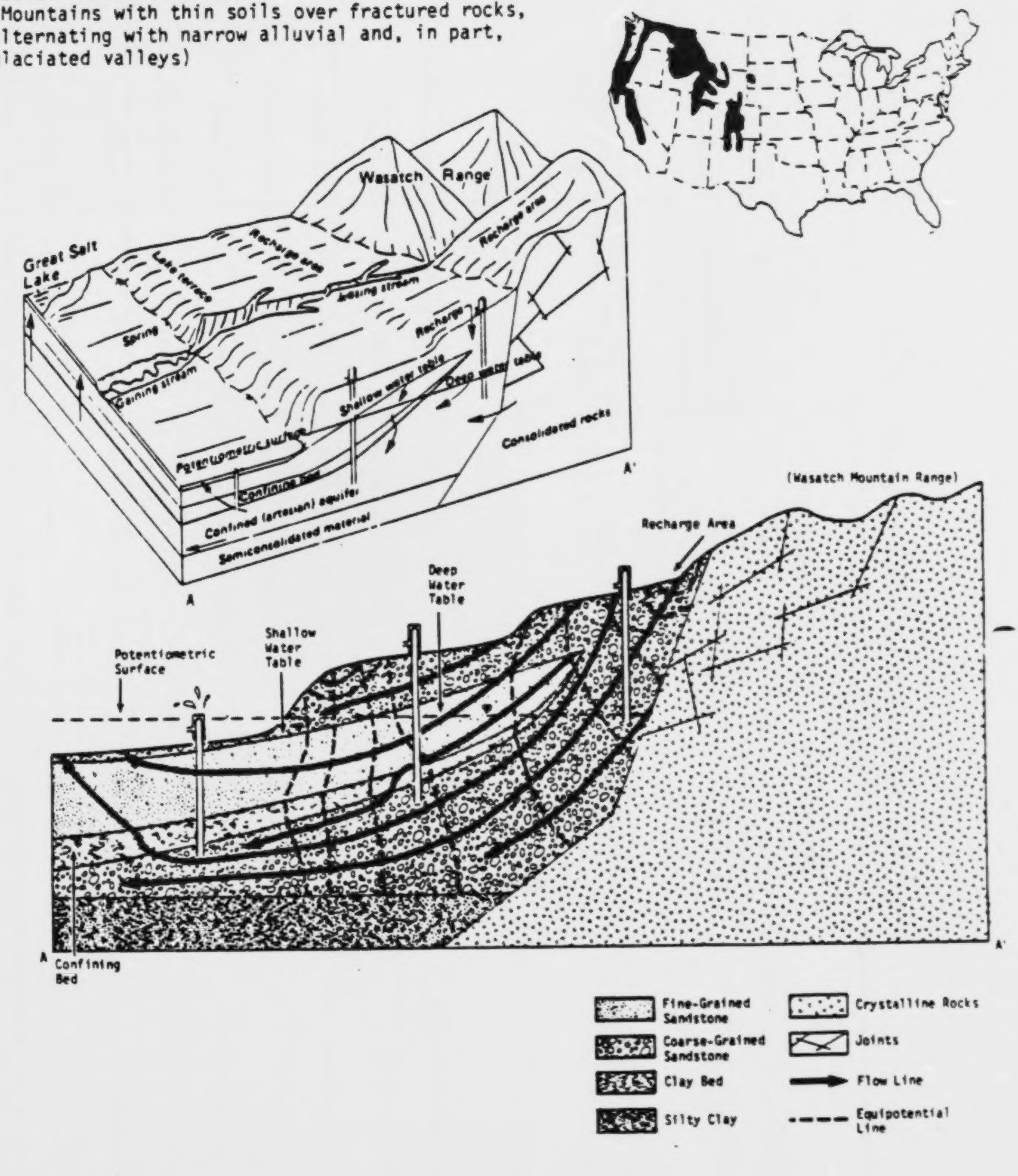

Wasatch Range
Great Salt Lake
Lake terrace
Recharge area
Losing stream
Recharge area
Spring
Recharge
Gaining stream
Shallow water table
Deep water table
Consolidated rocks
Potentiometric surface
Confining bed
Confined (artesian) aquifer
Semiconsolidated material
A
A'
(Wasatch Mountain Range)
Recharge Area
Deep Water Table
Shallow Water Table
Potentiometric Surface
A
Confining Bed
A'
Fine-Grained Sandstone
Coarse-Grained Sandstone
Clay Bed
Silty Clay
Crystalline Rocks
Joints
Flow Line
Equipotential Line

Figure 10-3. Western Mountain Ranges

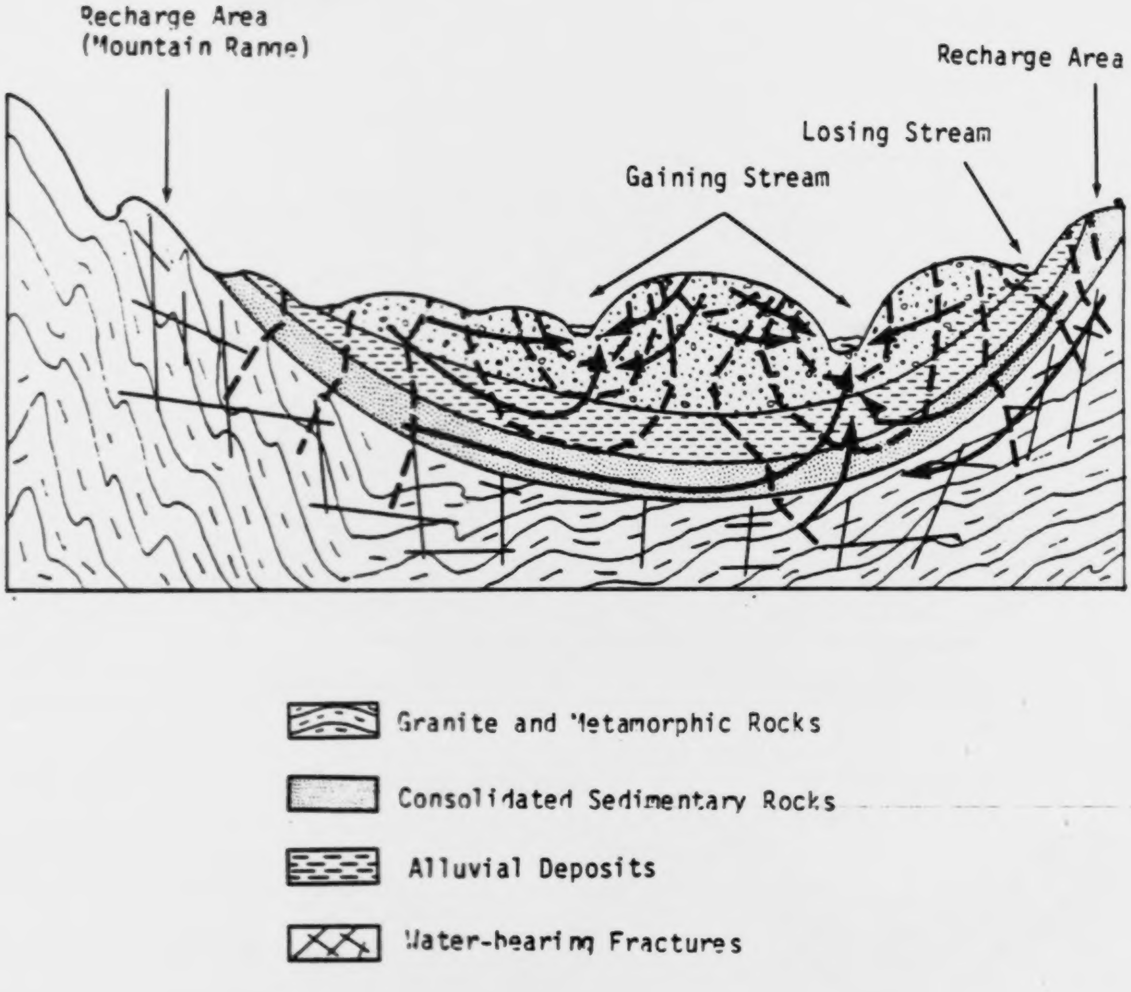
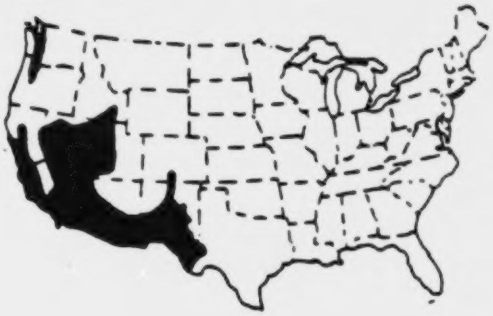

Recharge Area
(Mountain Range)
Recharge Area
Losing Stream
Gaining Stream
Granite and Metamorphic Rocks
Consolidated Sedimentary Rocks
Alluvial Deposits
Water-bearing Fractures

Figure 10-3. Western Mountain Ranges (continued)

ALLUVIAL BASINS
(Thick alluvial deposits in basins and valleys
bordered by mountains)



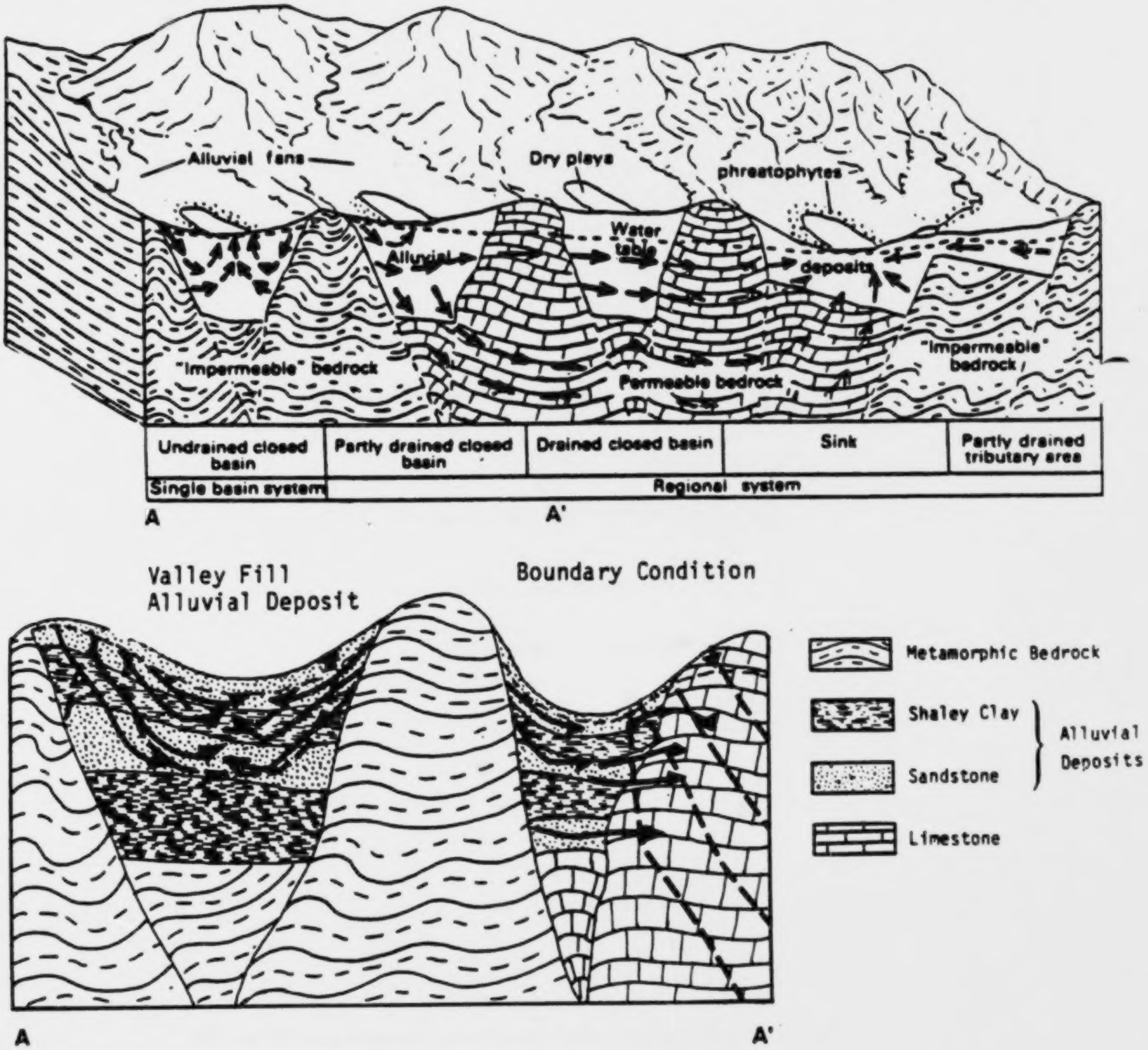

Alluvial fans
Dry playa
phreatophytes
Water table
Alluvial
deposits
"Impermeable" bedrock
Permeable bedrock
"Impermeable" bedrock
Undrained closed basin
Partly drained closed basin
Drained closed basin
Sink
Partly drained tributary area
Single basin system
Regional system
A
A'
Valley Fill
Alluvial Deposit
Boundary Condition
Metamorphic Bedrock
Shaley Clay
Sandstone
Alluvial Deposits
Limestone
A
A'

Figure 10-4. Alluvial Basins

Example of an undetected structurally complex uppermost aquifer.

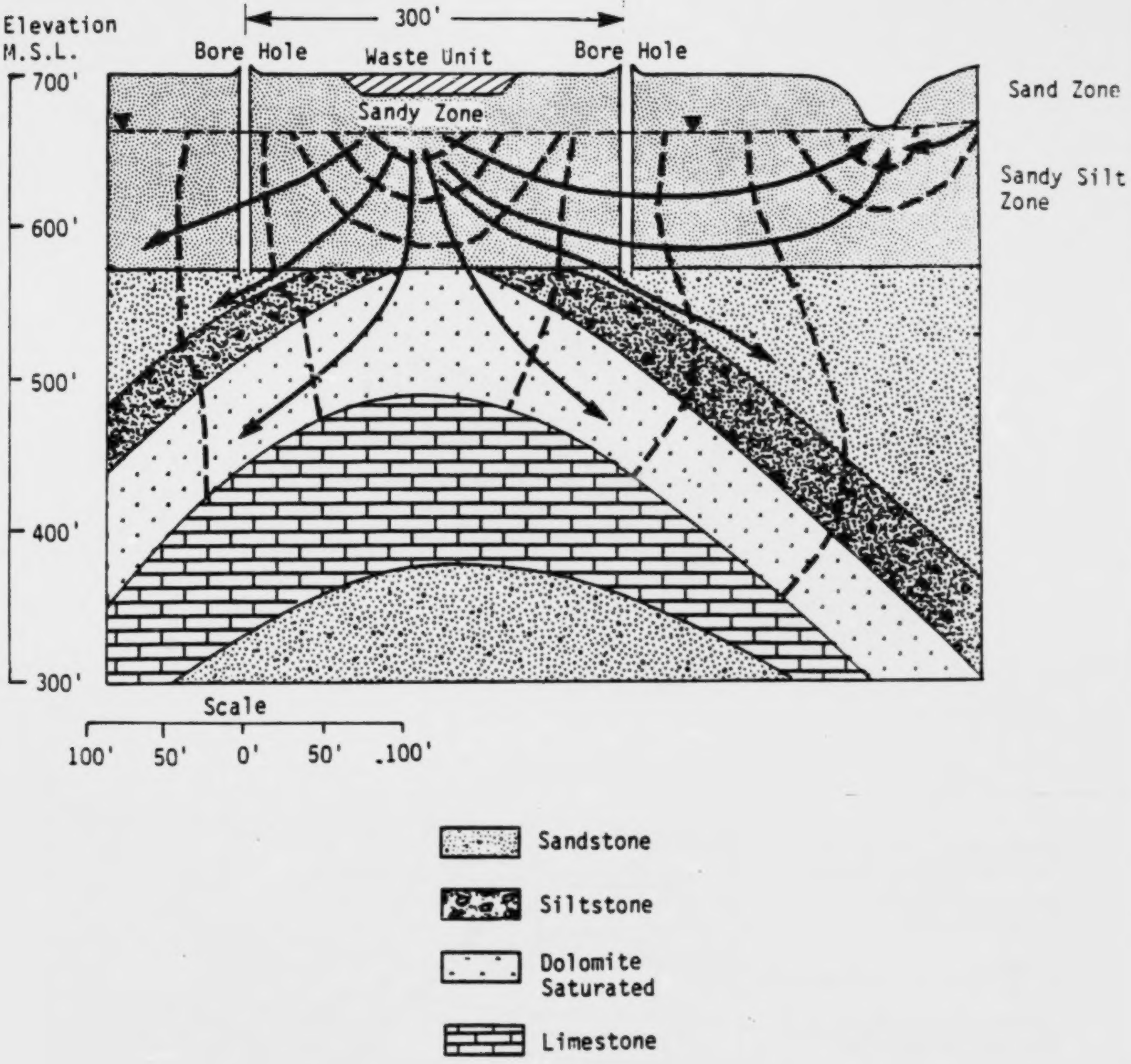
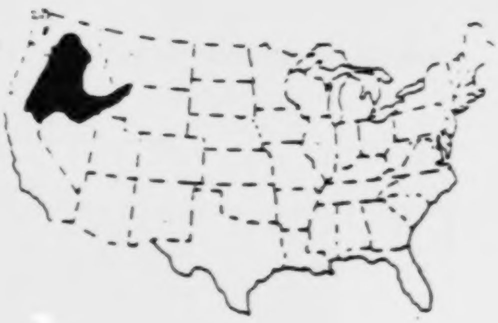
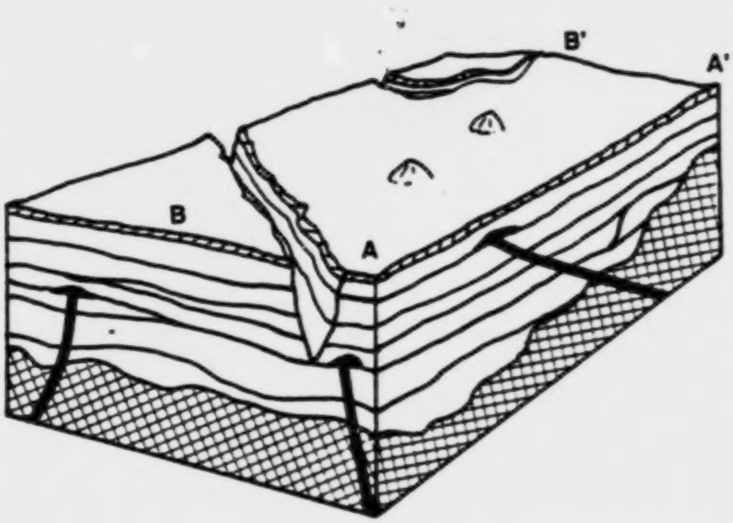

300'
Elevation
M.S.L.
Bore Hole
Waste Unit
Bore Hole
700'
Sand Zone
Sandy Zone
Sandy Silt
Zone
600'
500'
400'
300'
Scale
100'
50'
0'
50'
100'
Sandstone
Siltstone
Dolomite
Saturated
Limestone

Figure 10-4. Alluvial Basins (continued)

COLUMBIA LAVA PLATEAU
(Thick sequence of lava flows irregularly interbedded with thin unconsolidated deposits and overlain by thin soils)





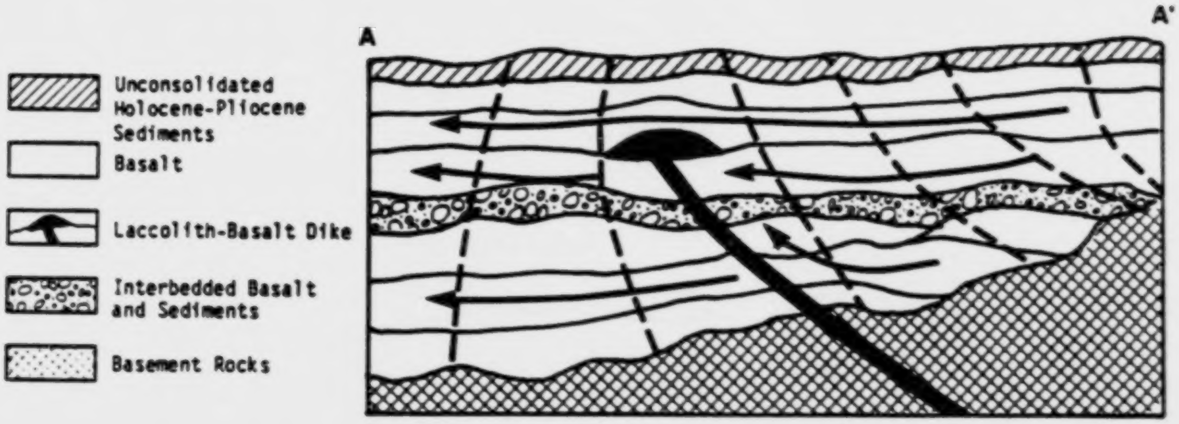
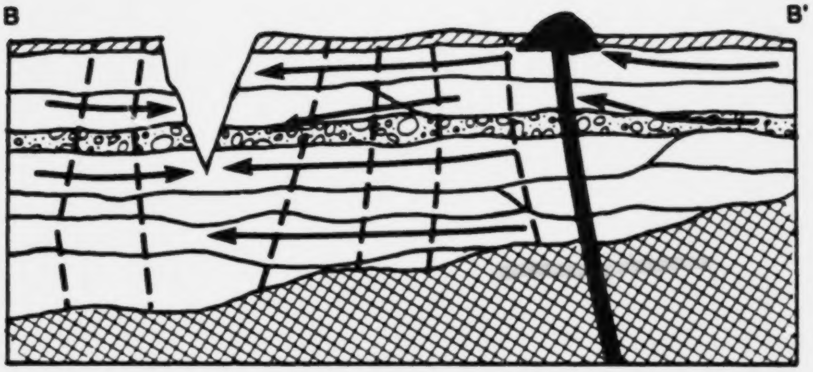
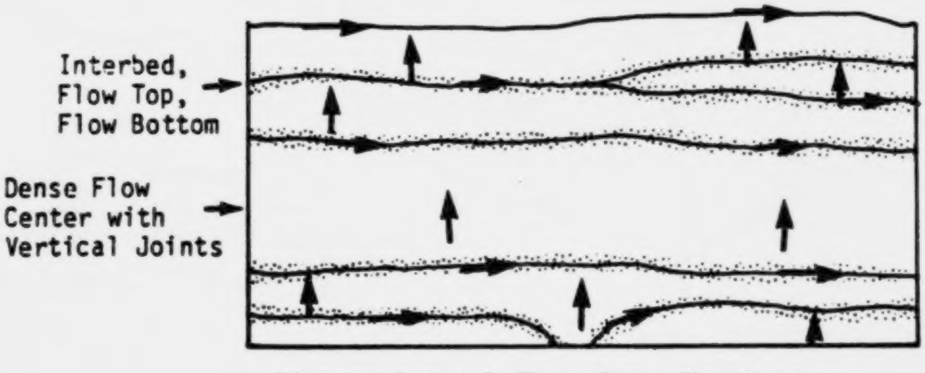

A
A'
Unconsolidated Holocene-Pliocene Sediments
Basalt
Laccolith-Basalt Dike
Interbedded Basalt and Sediments
Basement Rocks

Figure 10-5. Columbia Lava Plateau



Ground Water Flow Path
(No scale intended)

Note: Assume hydraulic heads increase with depth.


Interbed,
Flow Top,
Flow Bottom
Dense Flow
Center with
Vertical Joints

- High horizontal flow along flow tops
- Low vertical leakage through basalt interiors

Figure 10-5. Columbia Lava Plateau (continued)

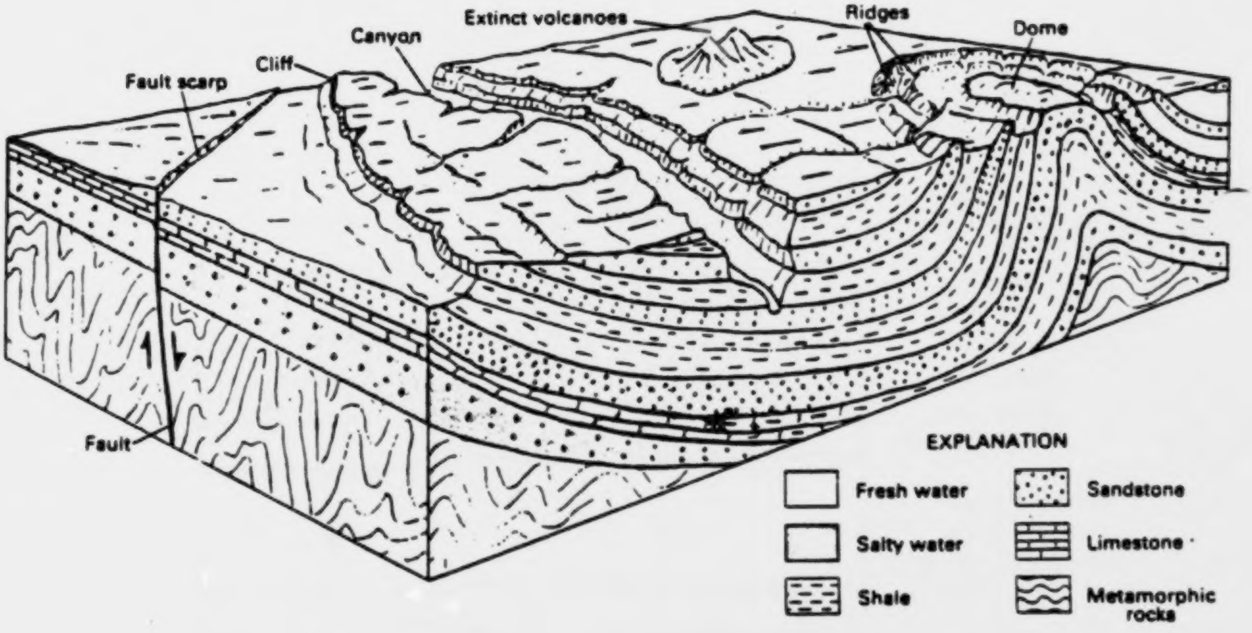
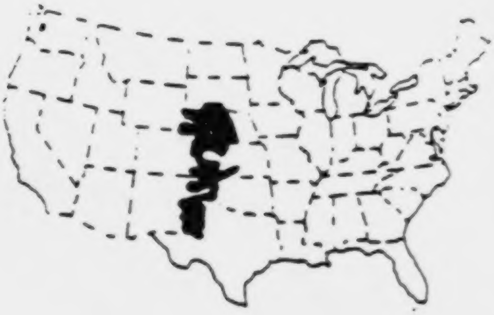
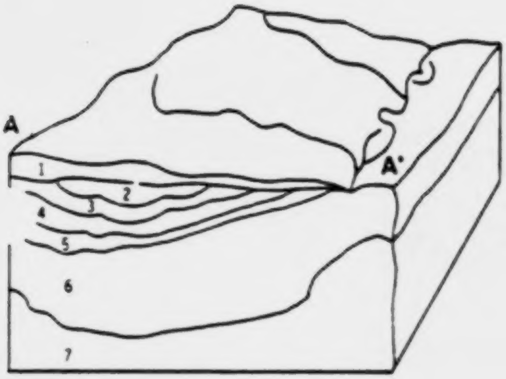

Extinct volcanoes
Ridges
Dome
Canyon
Cliff
Fault scarp
Fault
EXPLANATION
Fresh water
Salty water
Shale
Sandstone
Limestone
Metamorphic rocks

Figure 10-6. Colorado Plateau

HIGH PLAINS
(Thick alluvial deposits over fractured sedimentary rocks)





1 Paleovalley Alluvial Aquifers

2 High Plains Aquifer System

3 Niobrara Sandstone Aquifer

4 Pierre Shale Aquitard

5 Dakota Sandstone Aquifer

6 Undifferentiated Aquifers in Cretaceous Rocks

7 Undifferentiated Aquifers in Paleozoic Rocks

Generalized local ground water regime for site within the High Plains Region

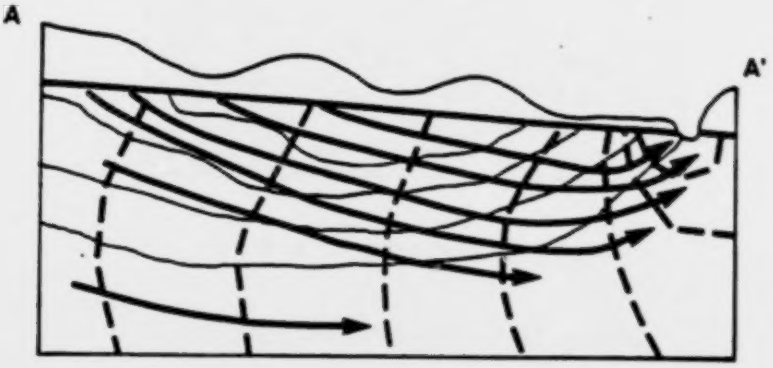
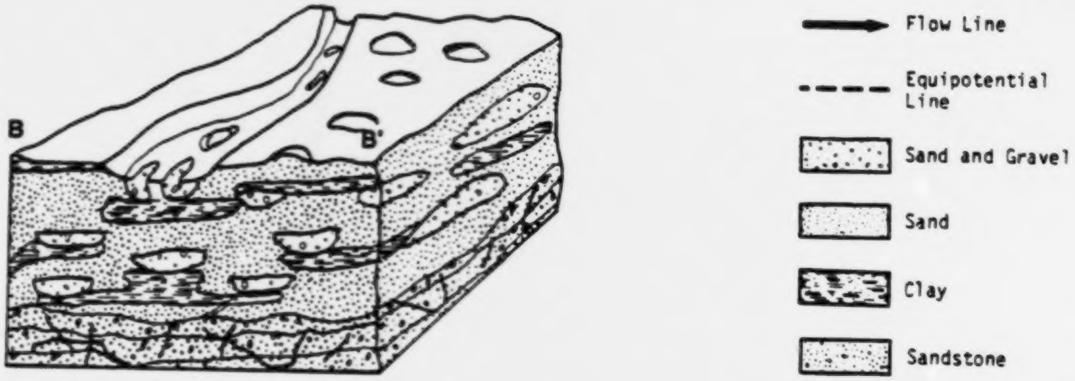
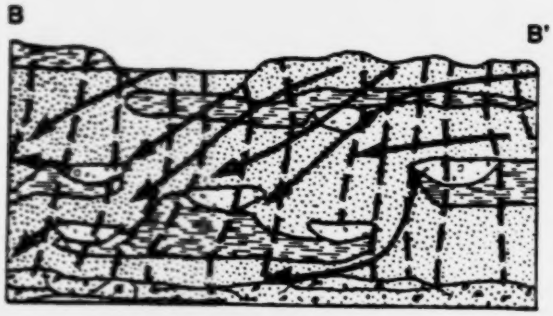


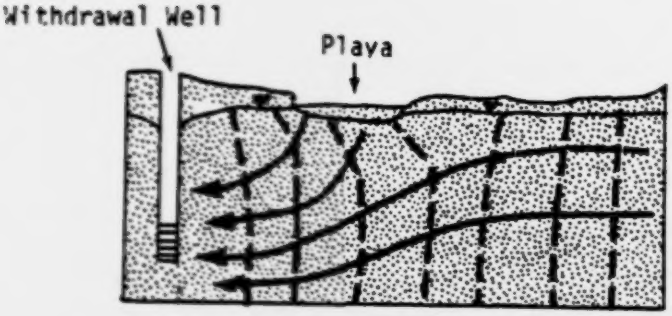
Figure 10-7. High Plains

Ground water flow in sandstone and clay lenses


B
B'
Flow Line
Equipotential Line
Sand and Gravel
Sand
Clay
Sandstone



Generalized Regional Flow


Withdrawal Well
Playa

Western Texas
(Recharge centered at playas)

Figure 10-7. High Plains (continued)

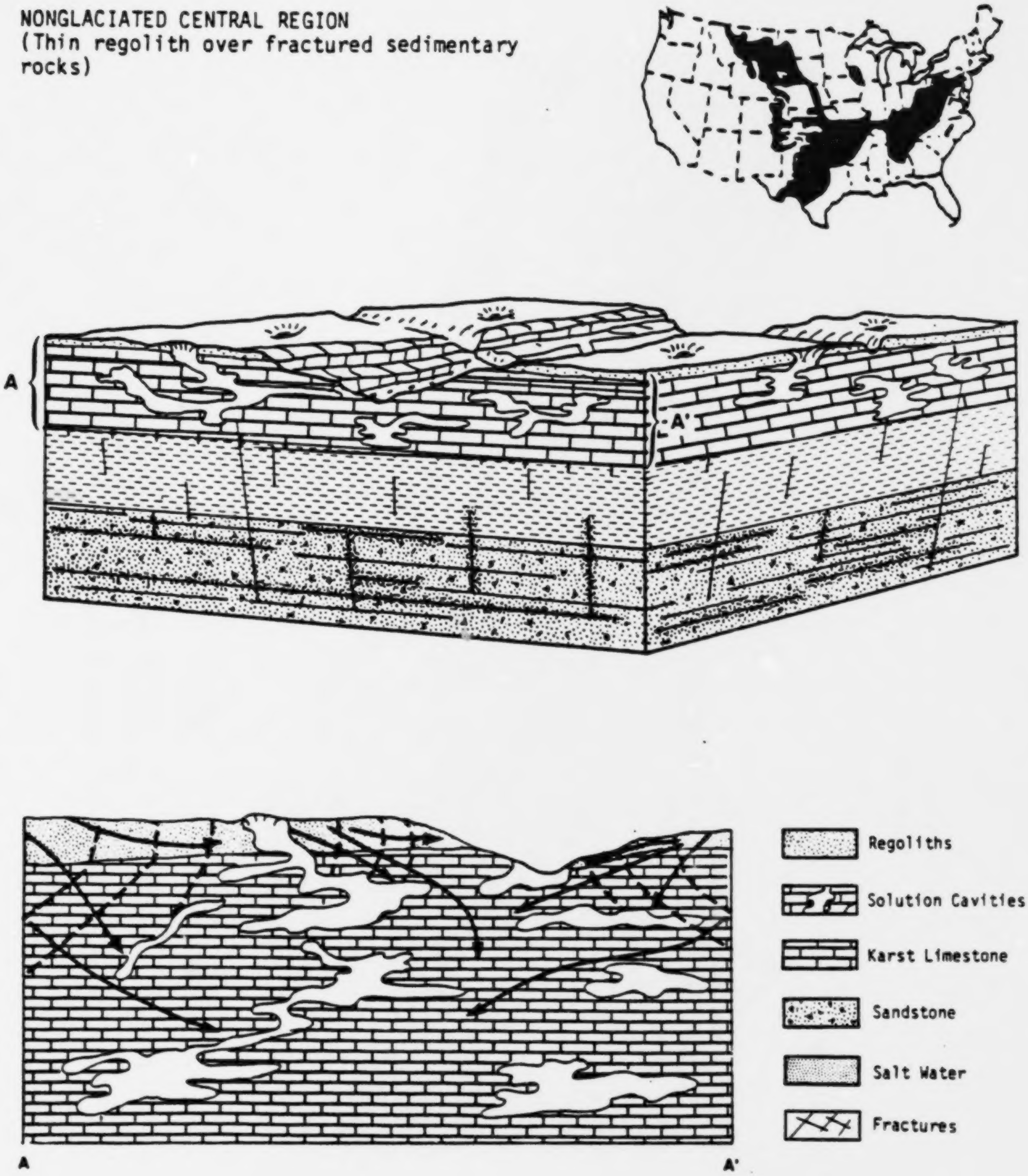

NONGLACIATED CENTRAL REGION
(Thin regolith over fractured sedimentary rocks)
A
A'
A
A'
Regoliths
Solution Cavities
Karst Limestone
Sandstone
Salt Water
Fractures

Figure 10-8. Non-glaciated Central

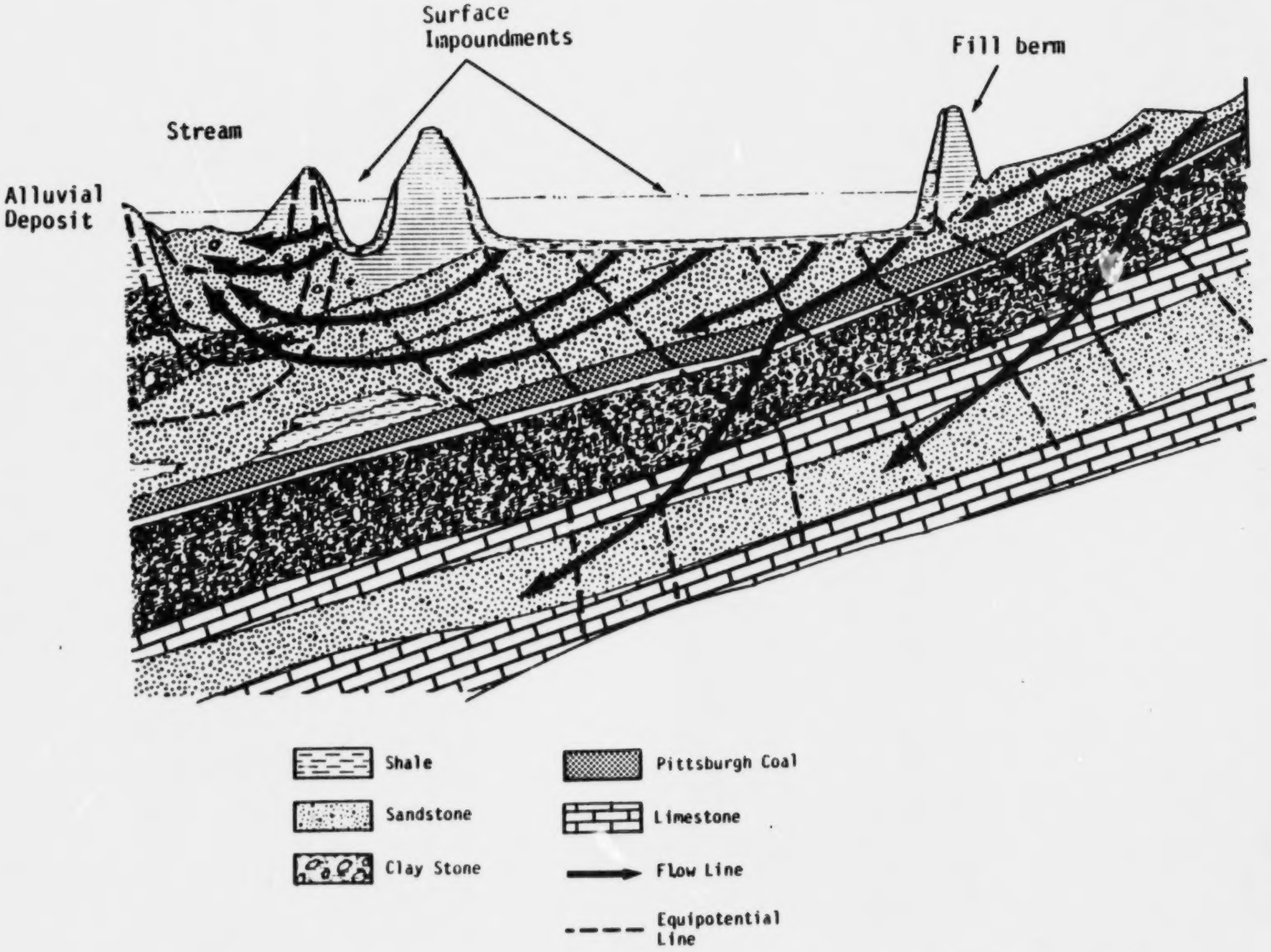
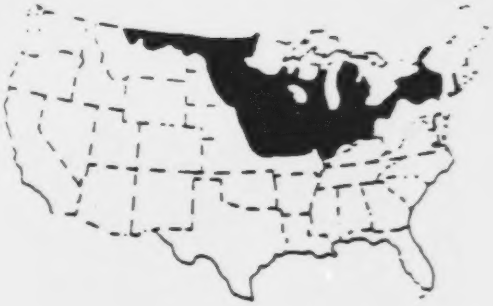

Surface Impoundments
Fill berm
Stream
Alluvial Deposit
Shale
Sandstone
Clay Stone
Pittsburgh Coal
Limestone
Flow Line
Equipotential Line

Figure 10-8. Example of a surface impoundment site in Non-Glaciated Central Region (continued)

GLACIATED CENTRAL REGION
(Glacial deposits over fractured sedimentary rocks)



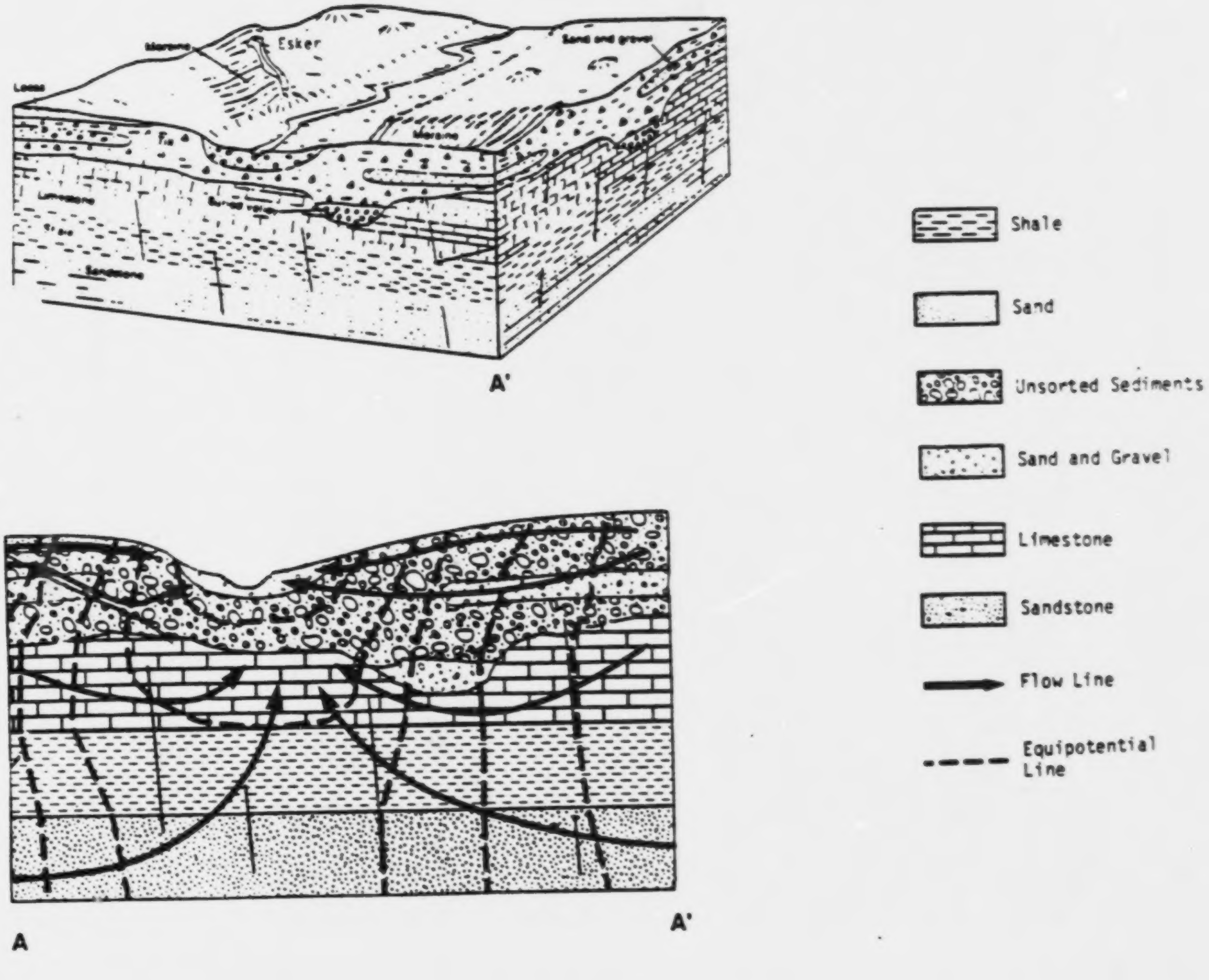

Moraine
Esker
Sand and gravel
Loess
Till
Moraine
Limestone
Buried valley
Shale
Sandstone
A'
Shale
Sand
Unsorted Sediments
Sand and Gravel
Limestone
Sandstone
Flow Line
Equipotential Line
A
A'

Figure 10-9. Glaciated Central

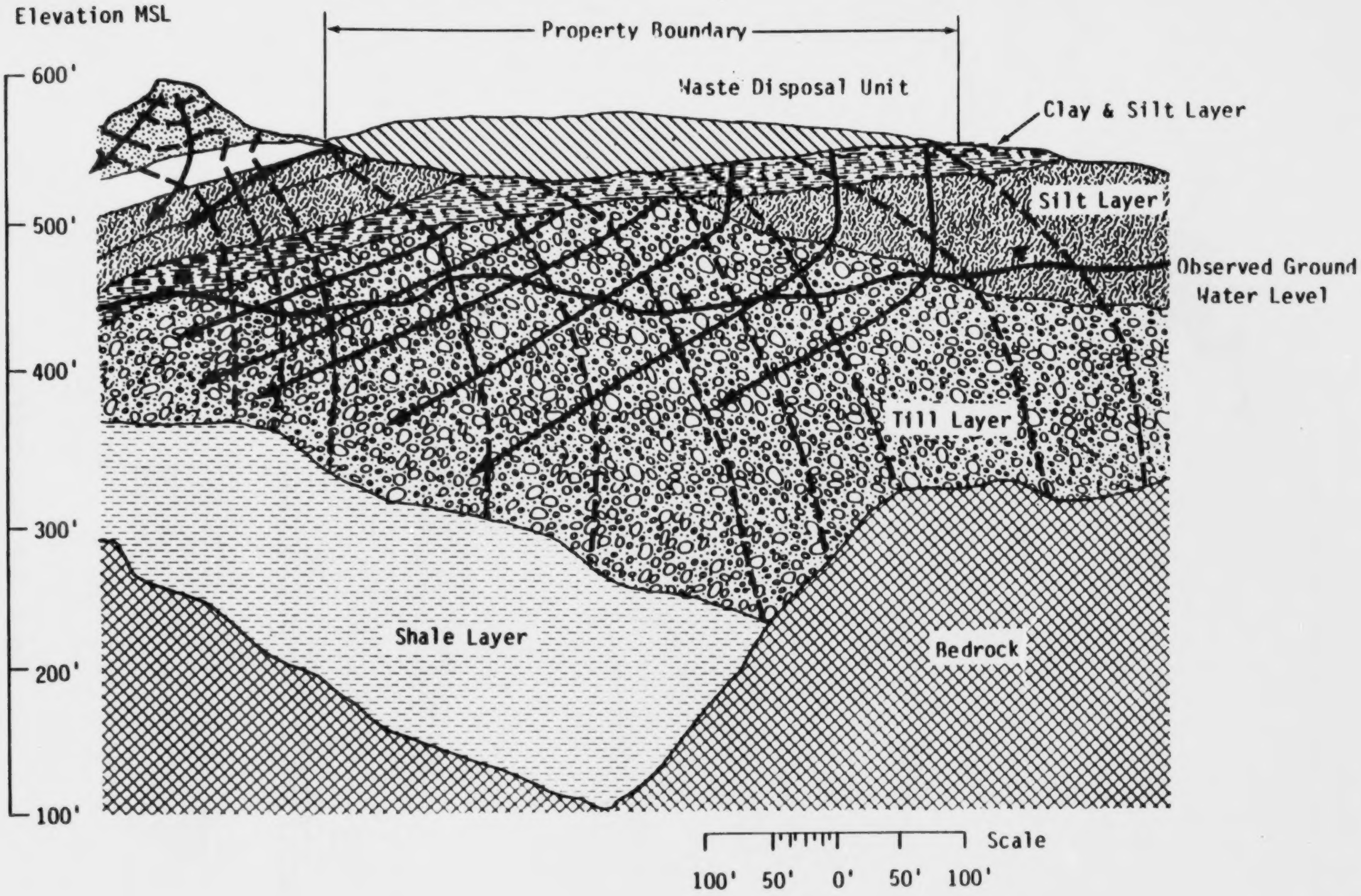
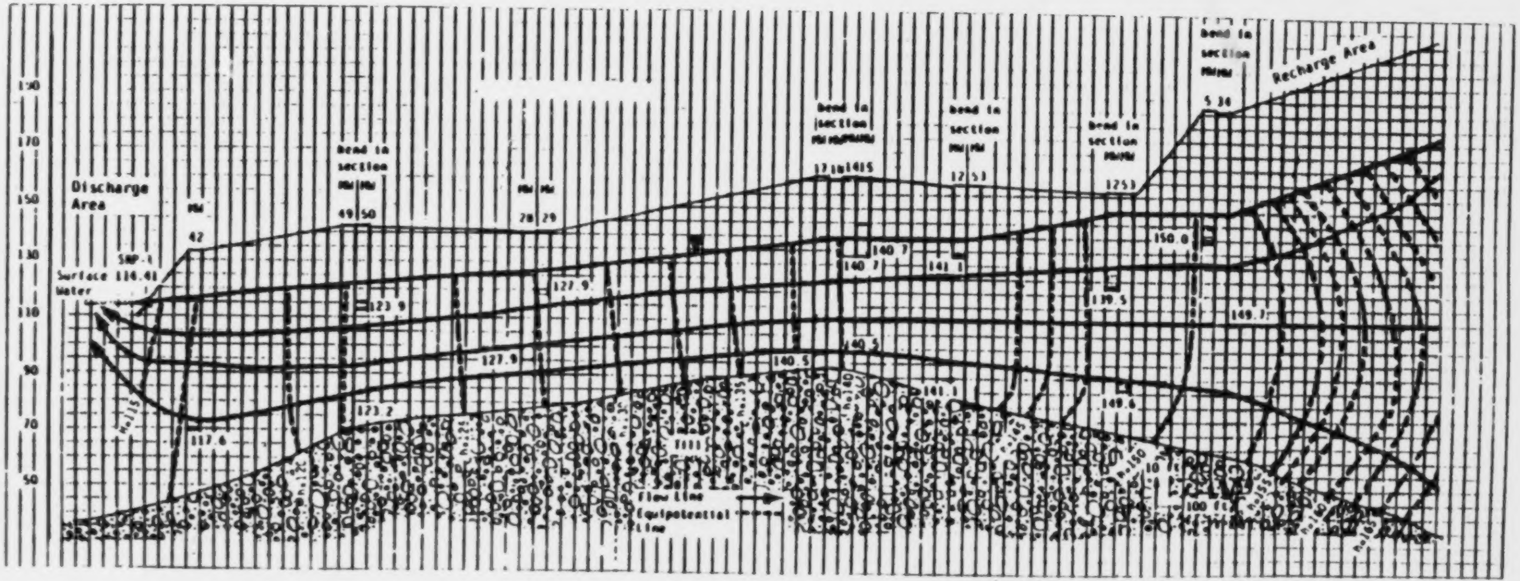

Elevation MSL
600'
500'
400'
300'
200'
100'
Property Boundary
Waste Disposal Unit
Clay & Silt Layer
Silt Layer
Observed Ground Water Level
Till Layer
Shale Layer
Bedrock
100'
50'
0'
50'
100'
Scale

Figure 10-9. Glaciated Central (continued)

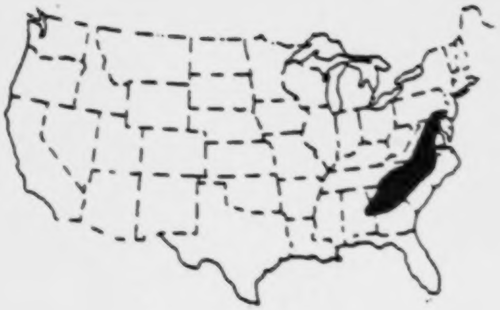
Example of a ground-water regime where till has a much lower hydraulic conductivity than overlying deltaic deposits

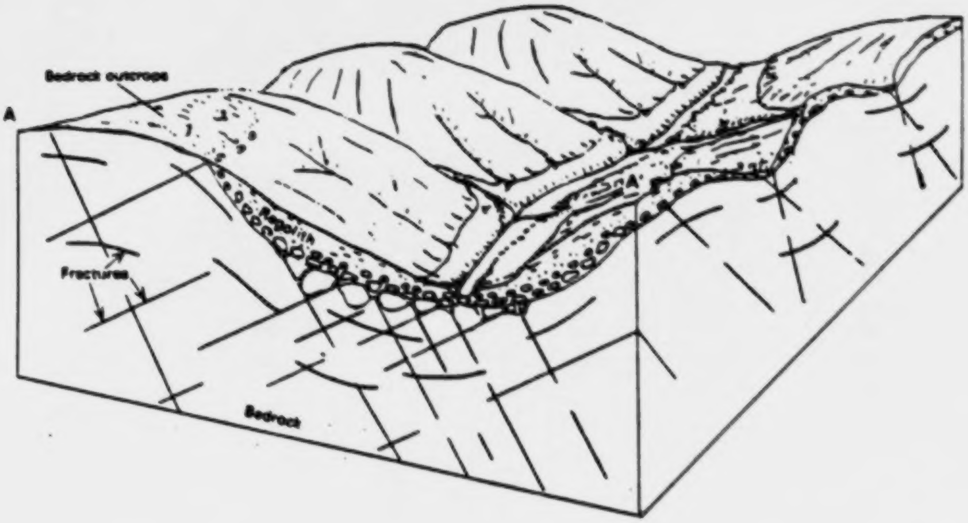

190
170
150
130
110
90
70
50
Discharge Area
SWP-1
Surface Water
114.41
MW 42
bend in section
MW MW
49 50
MW MW
28 29
123.9
123.2
117.6
127.9
127.9
bend in section
17 16 14 15
140.7
140.7
140.5
140.5
bend in section
MW MW
12 53
141.1
141.1
bend in section
1253
139.5
149.6
150.0
bend in section
5 30
149.7
Recharge Area
100 ft
Flow Line
Equipotential Line

Reproduced from best available copy.

Figure 10-9. Glaciated Central (continued)

PIEDMONT BLUE RIDGE REGION
(Thick regolith over fractured crystalline and metamorphosed sedimentary rocks)




Bedrock outcrops
A
Regolith
A'
Fractures
Bedrock

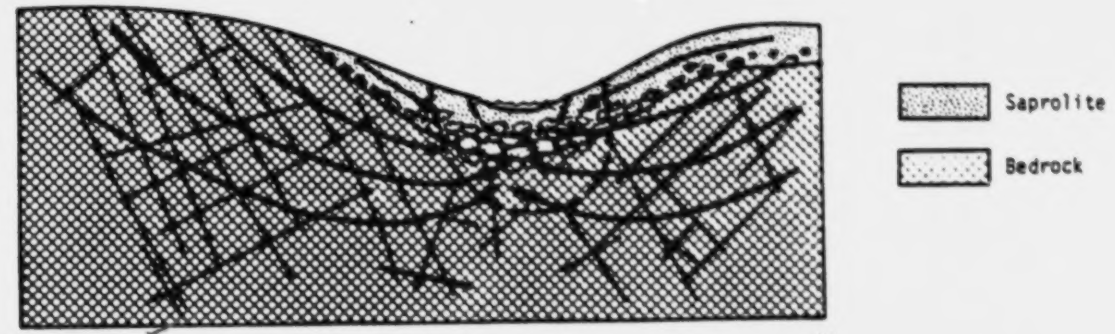

Saprolite
Bedrock
A
A'

Figure 10-10. Piedmont and Blue Ridge

NORTHEAST AND SUPERIOR UPLANDS
(Glacial deposits over fractured
crystalline rocks)

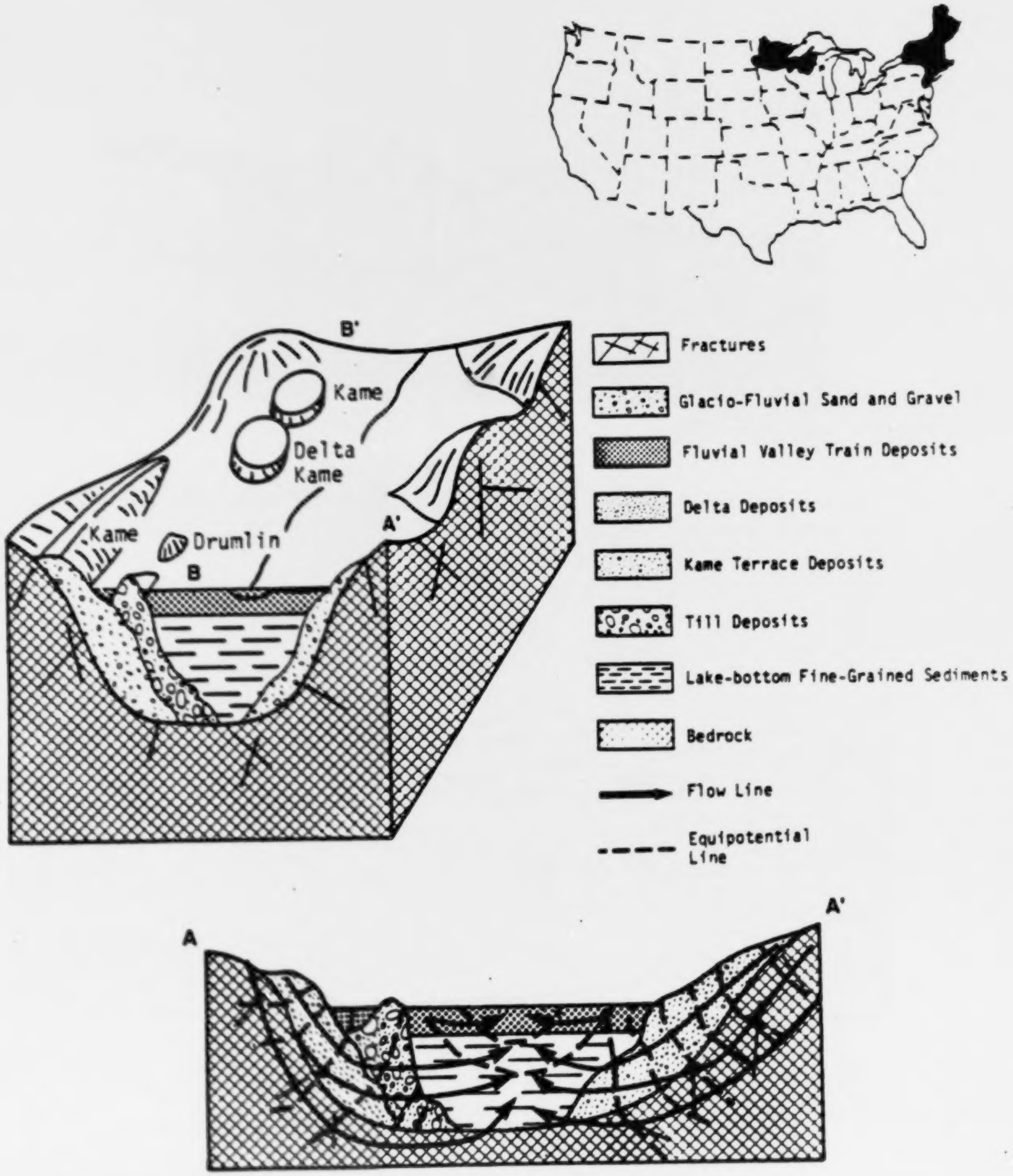
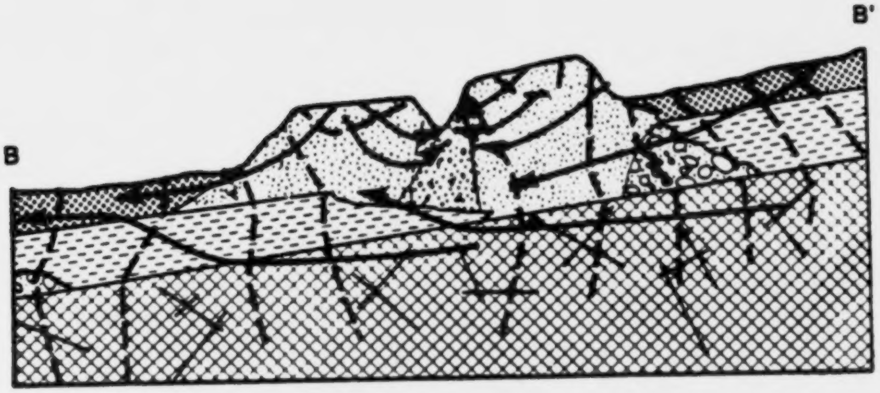

B'
Kame
Delta
Kame
A
Kame
Drumlin
A'
B
Fractures
Glacio-Fluvial Sand and Gravel
Fluvial Valley Train Deposits
Delta Deposits
Kame Terrace Deposits
Till Deposits
Lake-bottom Fine-Grained Sediments
Bedrock
Flow Line
Equipotential Line
A
A'

Figure 10-11. Northeast and Superior Uplands



Generalized local ground water regime within the Northeast and Superior Uplands Region

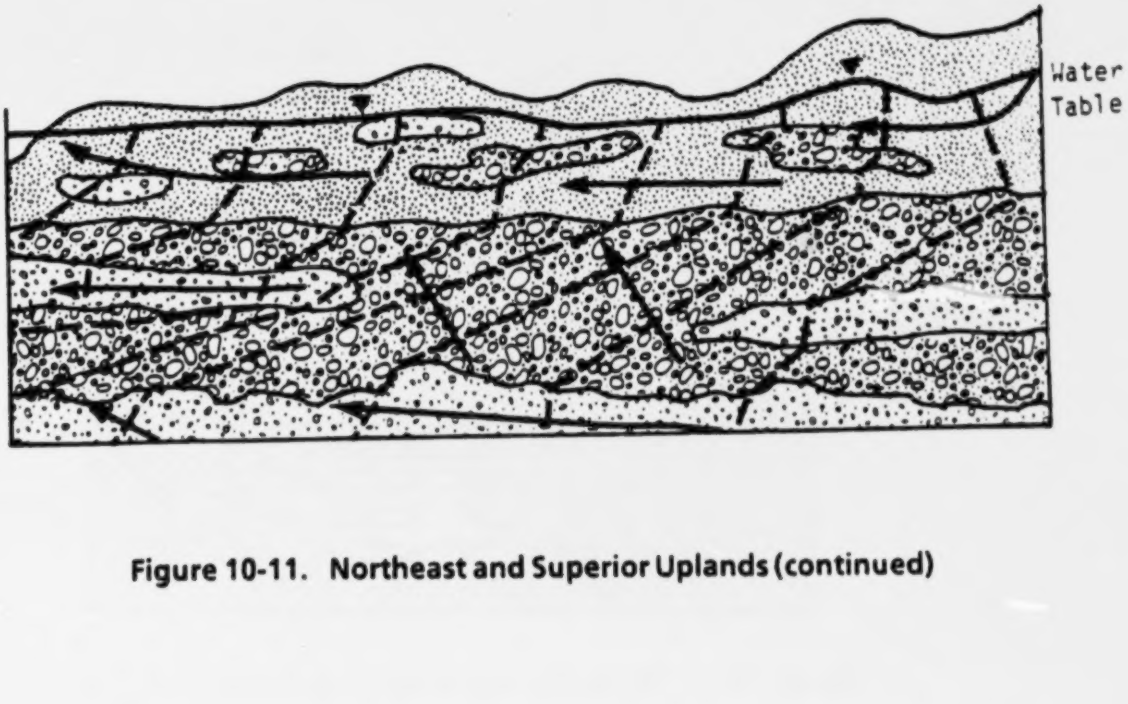
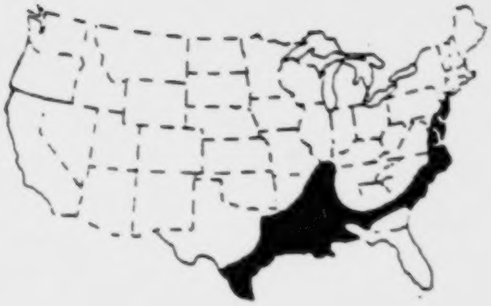
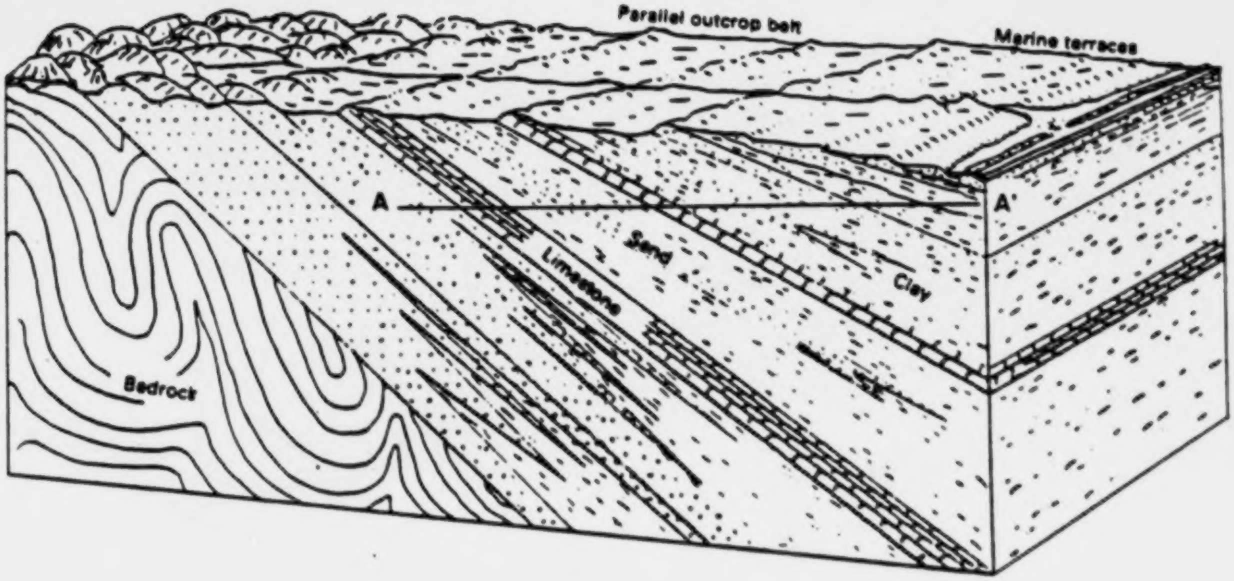


Figure 10-11. Northeast and Superior Uplands (continued)

ATLANTIC AND GULF COASTAL PLAIN
(Complexly interbedded sand, silt, and clay)




Parallel outcrop belt
Marine terraces
A
A'
Sand
Clay
Limestone
Bedrock

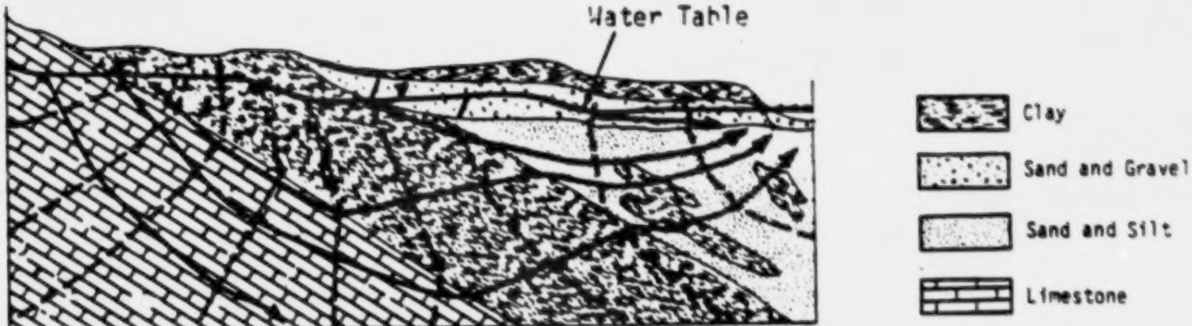
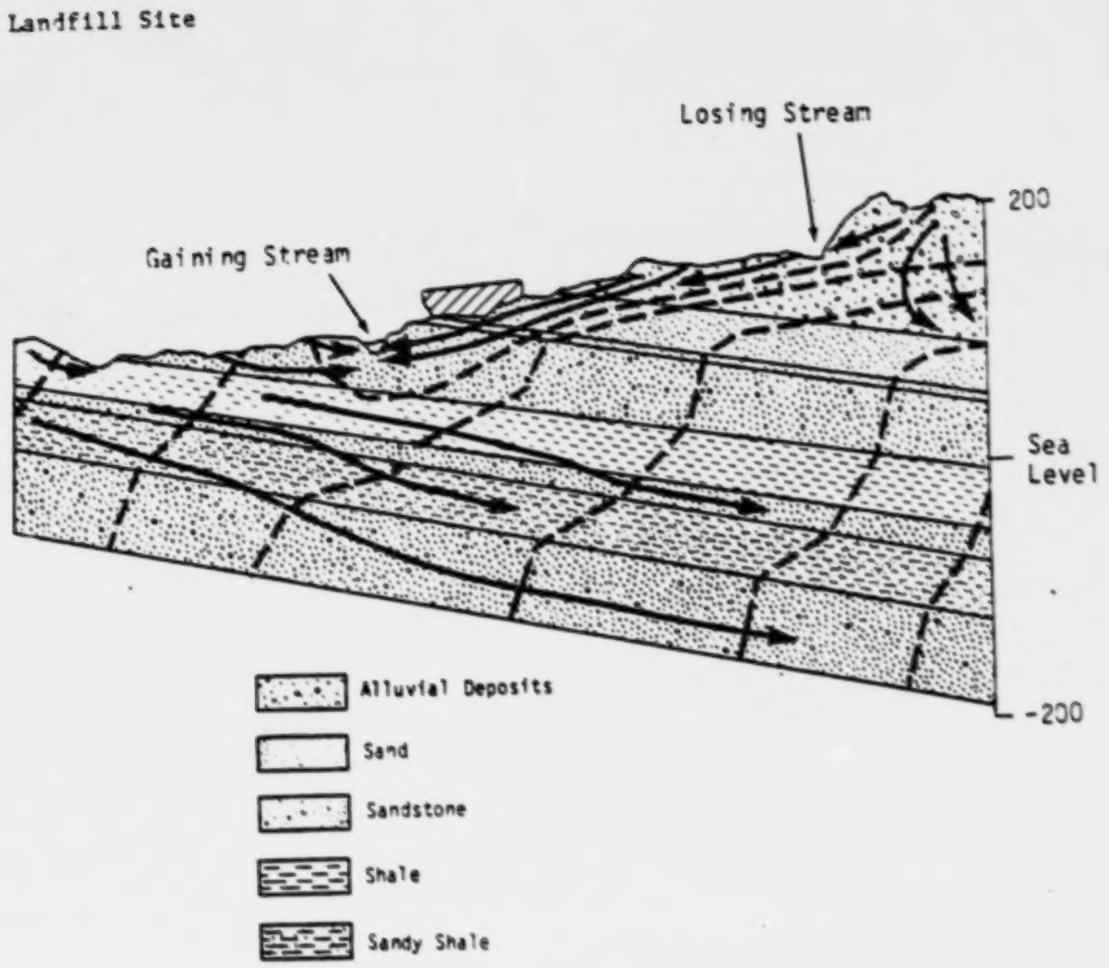

Water Table
A
A'
Clay
Sand and Gravel
Sand and Silt
Limestone

Figure 10-12. Atlantic and Gulf Coastal Plain


Landfill Site
Losing Stream
Gaining Stream
200
Sea Level
-200
Alluvial Deposits
Sand
Sandstone
Shale
Sandy Shale

Note: Regional flow based on high recharge in hills which are not shown in this diagram.

Figure 10-12. Atlantic and Gulf Coastal Plain (continued)

Proposed landfill

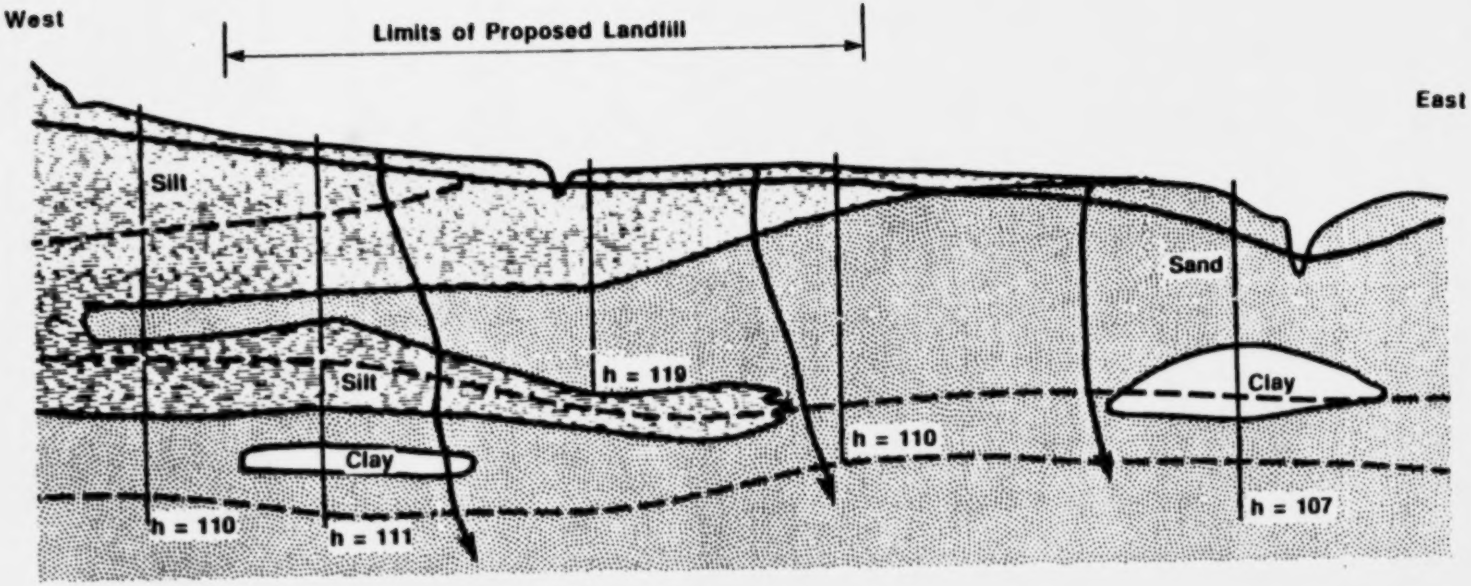
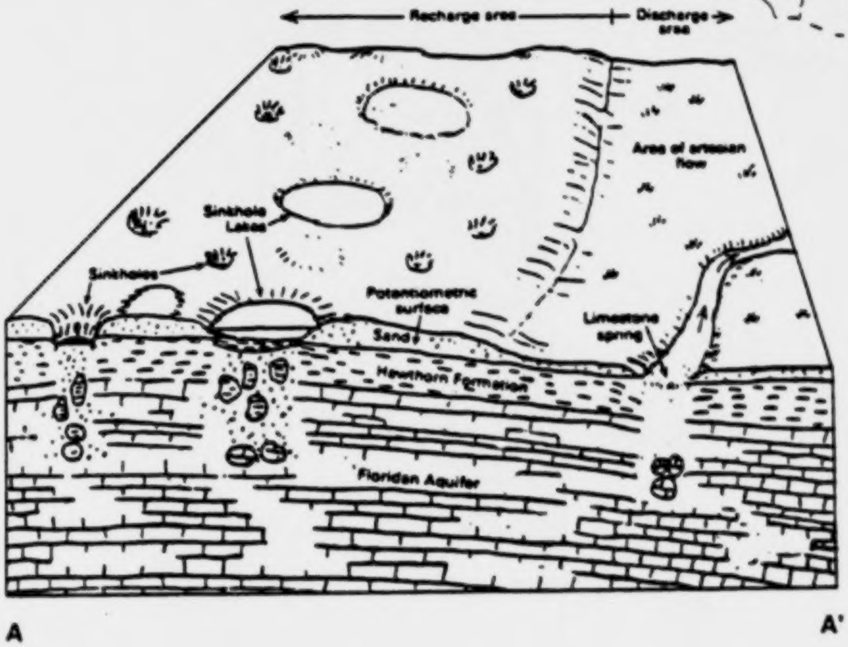
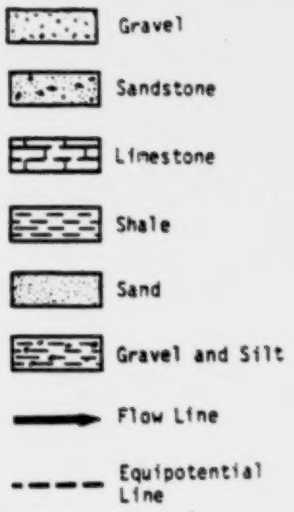

West
Limits of Proposed Landfill
East
Silt
Sand
h = 119
Silt
Clay
h = 110
Clay
h = 110
h = 111
h = 107

Figure 10-12. Atlantic and Gulf Coastal Plain (continued)

SOUTHEAST COASTAL PLAIN
(Thick layers of sand and clay over semi-consolidated carbonate rocks)


Recharge area
Discharge area
Area of artesian flow
Sinkhole Lakes
Sinkholes
Potentiometric surface
Sand
Limestone spring
Hawthorn Formation
Floridan Aquifer
A
A'


Gravel
Sandstone
Limestone
Shale
Sand
Gravel and Silt
Flow Line
Equipotential Line

Solution Limestone

Cross-section with highly generalized flow path lines and equipotential lines. Actual condition in Karst terrain may not be definable due to fractures and solution channel flow.

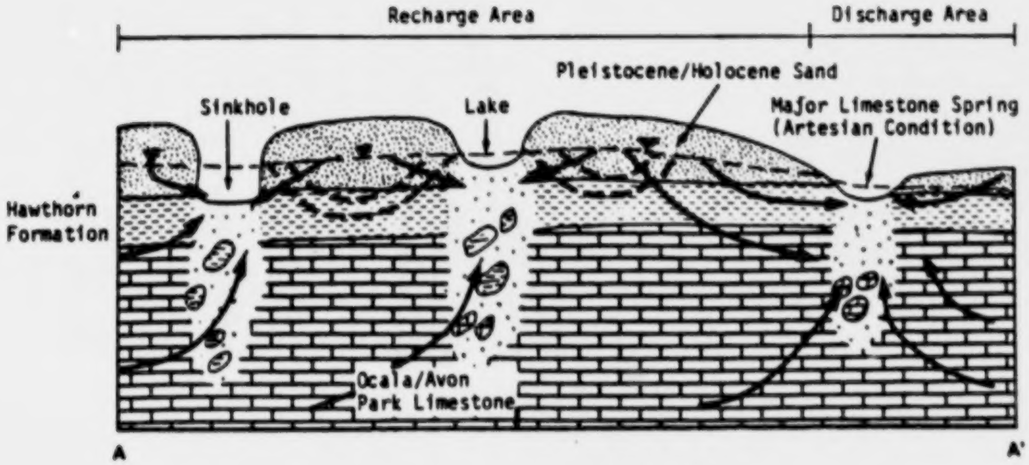
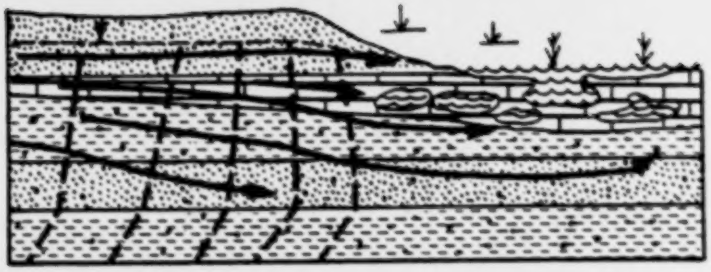
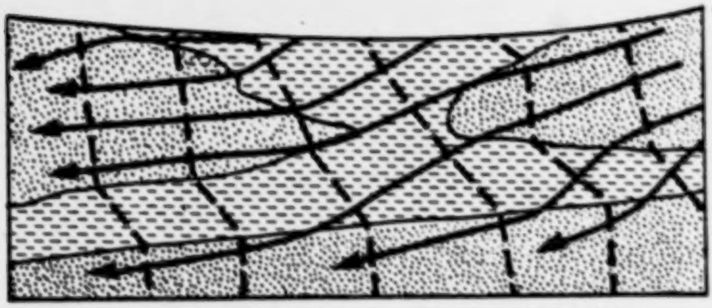

Recharge Area
Discharge Area
Pleistocene/Holocene Sand
Sinkhole
Lake
Major Limestone Spring (Artesian Condition)
Hawthorn Formation
Ocala/Avon Park Limestone
A
A'

Figure 10-13. Southeast Coastal Plain

Swamp



Beaches and Bars



- Highly permeable due to water-washed sands.
- Sand deposits serve as a source of recharge to the underlying unconsolidated coastal deposits.

Figure 10-13. Southeast Coastal Plain (continued)

A generalized local ground water flow in Karst Limestone terrain

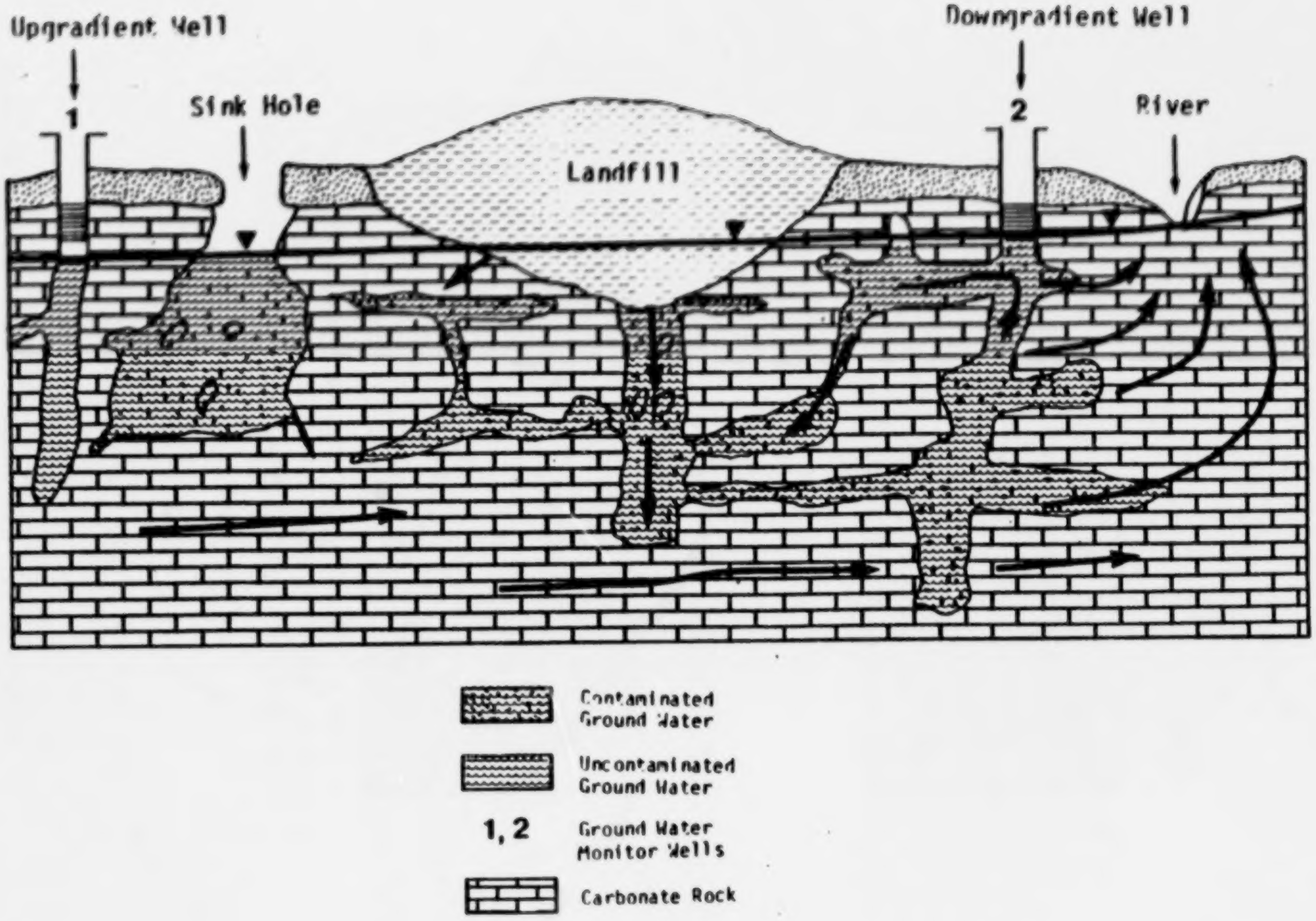

Upgradient Well
1
Sink Hole
Landfill
Downgradient Well
2
River
Contaminated Ground Water
Uncontaminated Ground Water
1, 2
Ground Water Monitor Wells
Carbonate Rock

Figure 10-13. Southeast Coastal Plain (continued)

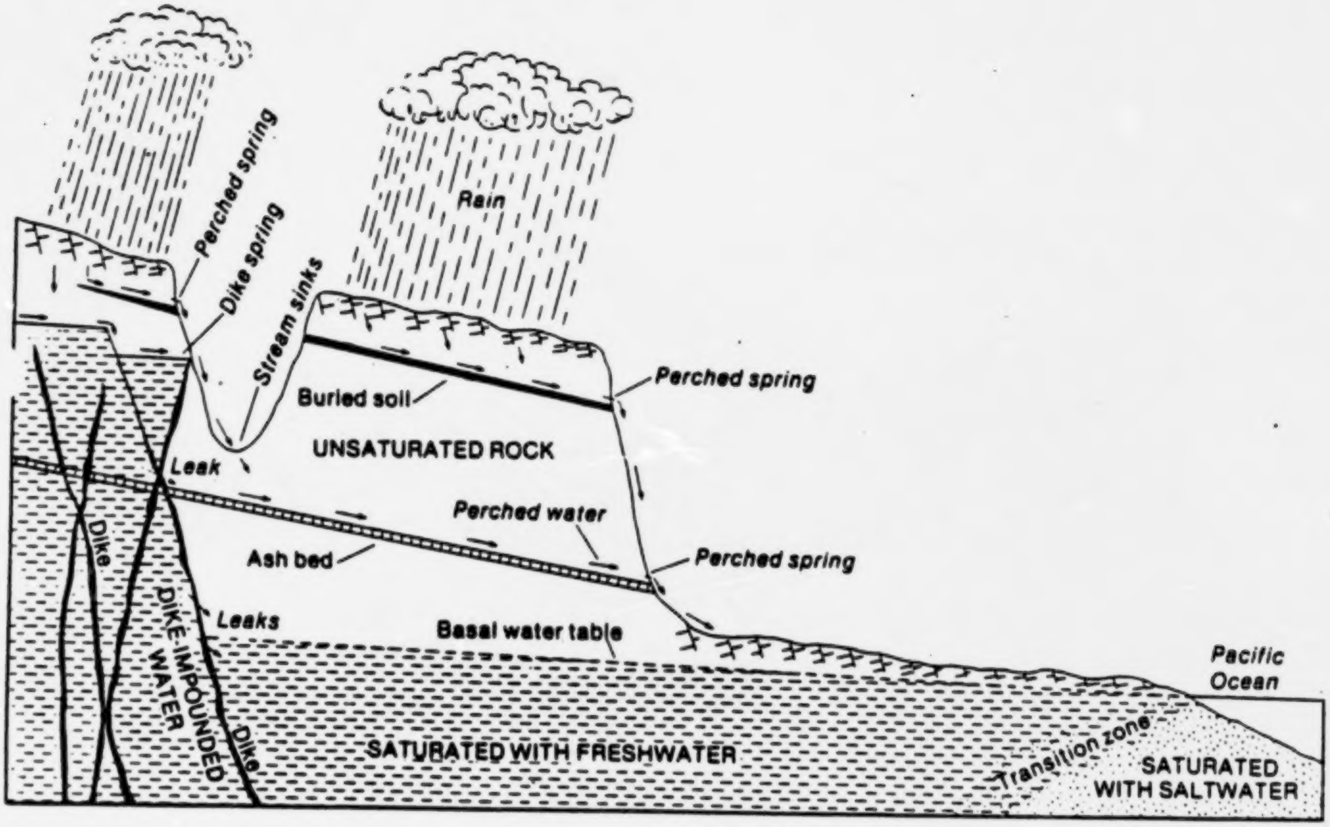

Rain
Perched spring
Dike spring
Stream sinks
Perched spring
Buried soil
UNSATURATED ROCK
Leak
Perched water
Perched spring
Ash bed
Dike
DIKE-IMPOUNDED WATER
Dike
Leaks
Basal water table
Pacific Ocean
SATURATED WITH FRESHWATER
Transition zone
SATURATED WITH SALTWATER

Figure 10-14. Hawaiian Islands

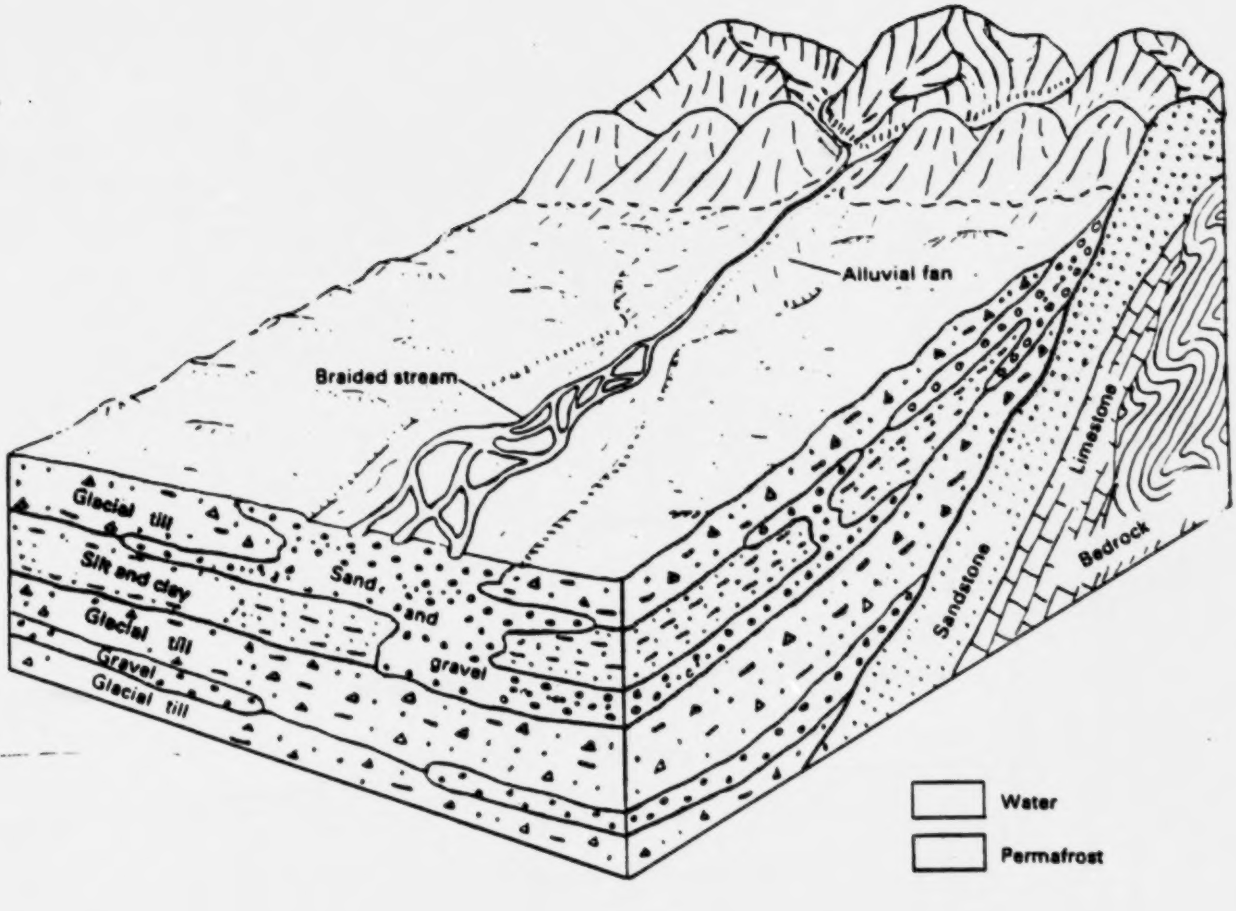
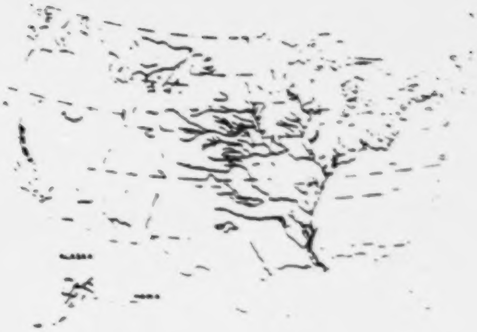

Alluvial fan
Braided stream
Glacial till
Silt and clay
Glacial till
Gravel
Glacial till
Sand and gravel
Sandstone
Limestone
Bedrock
Water
Permafrost

Figure 10-15. Alaska

ALLUVIAL VALLEYS
(Thick sand and gravel deposits beneath
floodplains and terraces of streams)



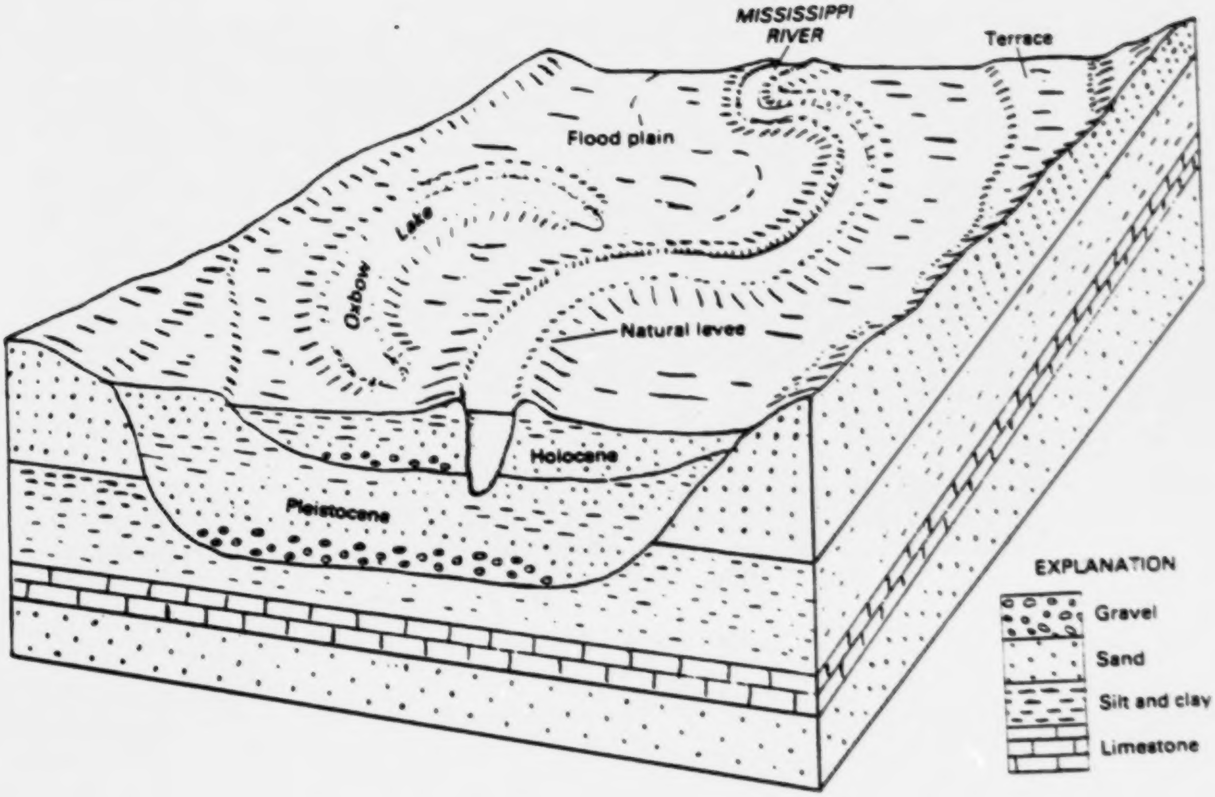
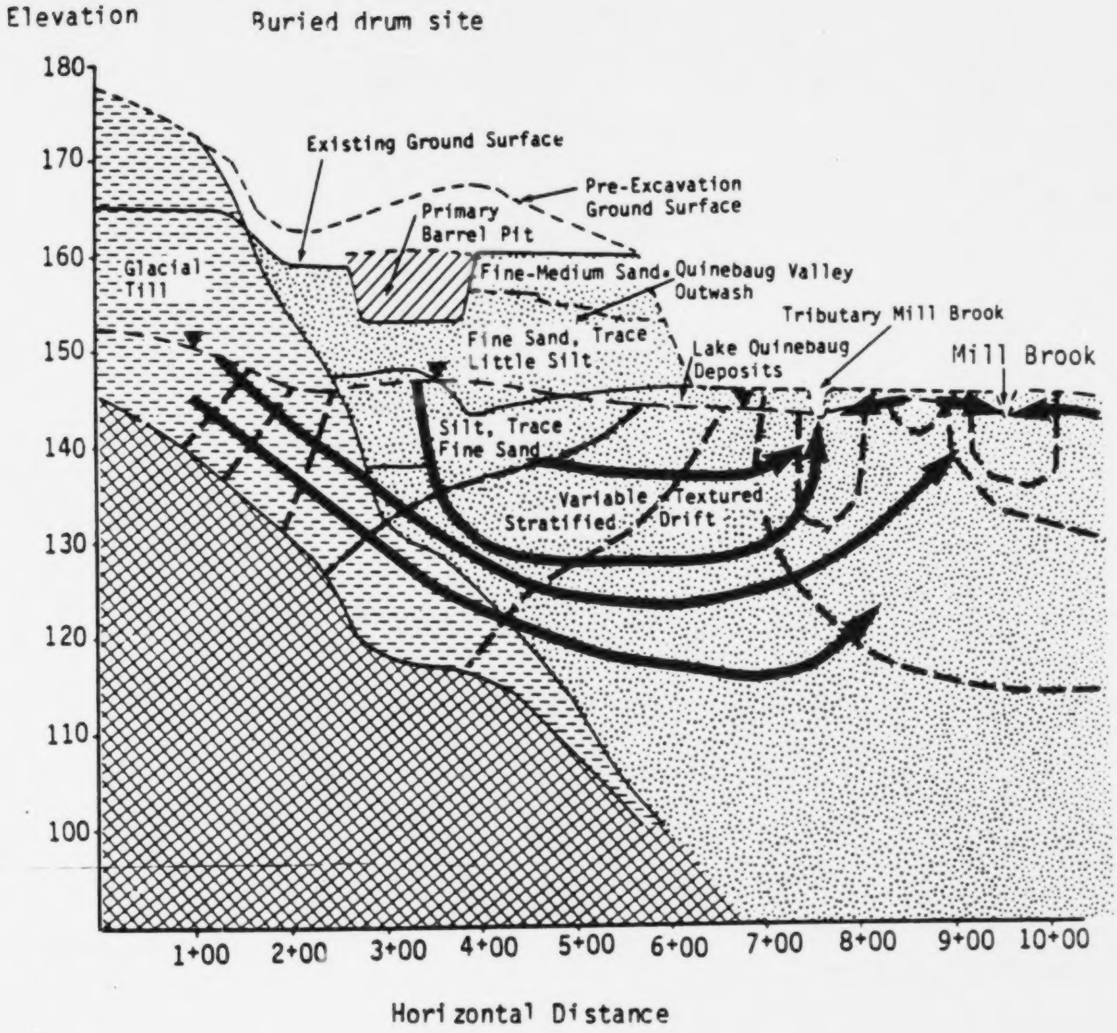

MISSISSIPPI RIVER
Terrace
Flood plain
Oxbow Lake
Natural levee
Holocene
Pleistocene
EXPLANATION
Gravel
Sand
Silt and clay
Limestone

Figure 10-16. Alluvial Valleys



Elevation
Buried drum site
180
170
160
150
140
130
120
110
100
Existing Ground Surface
Pre-Excavation Ground Surface
Primary Barrel Pit
Glacial Till
Fine-Medium Sand. Quinebaug Valley Outwash
Fine Sand, Trace Little Silt
Tributary Mill Brook
Lake Quinebaug Deposits
Mill Brook
Silt, Trace Fine Sand
Variable Textured Stratified Drift
1+00
2+00
3+00
4+00
5+00
6+00
7+00
8+00
9+00
10+00
Horizontal Distance

Figure 10-16. Alluvial Valleys (continued)

Basaltic bedrock is the major source of ground water within the Columbia Lava Plateau region. Volcanic bedrock yields water mainly from zones that are at the contacts of separate basalt flows. Permeability and hydraulic conductivity are much higher in these zones at the edges of the flows than in the center of the flows. (See Figure 10-5.) This is due, in part, to the rapid cooling and consequent fracturing of the top of each basalt flow.

The Colorado-Plateau region is underlain by fractured bedrock (See Figure 10-6). The main source of recharge is upland filtration and infiltration from local surface waters.

The High Plains region is underlain by thick alluvial deposits that comprise a productive and extensively developed aquifer system. The source of recharge to the aquifer system is precipitation except in western Texas where recharge is centered at playas (See Figure 10-7). In many areas, well discharge far exceeds recharge, and water levels are declining. The dominant features influencing ground-water flow in this region include the Ogalalla aquifer, the Pierre Shale, and the complex interbedded sand and clay lenses. Figure 10-7 provides generalized regional flow nets showing flow patterns through these features.

Thin regolith over fractured sedimentary rocks typifies the nature of the geology in the Nonglaciated Central region. (See Figure 10-8.) This region extends from the Rocky Mountains to the Appalachian Mountains. Water is transmitted primarily along horizontal fractures at bedding planes. Interconnected vertical fractures also can store a large amount of the ground water. An example of a flow net on a local scale is shown for ground-water flow through karst terrain. In karst terrain, ground water moves rapidly through solution cavities in limestone and the flow pathways are highly dependent on the configuration of fractures. Ground-water flow in the karst terrain does not follow Darcy's Law because the flow is turbulent rather than laminar. Thus, the flow path lines shown are highly idealized. An additional example of localized flow in this region is provided showing a surface impoundment site in Pennsylvania. Notice that ground-water discharges to surface water, a phenomenon typical of this region.

The topography of the Glaciated Central region is characterized by rolling hills and mountains in the eastern portion and flat to gently rolling terrain in the western portion. Glacial deposits vary in thickness within the region and are underlain by bedrock. Ground water occurs in the glacial deposits in pores between the grains and in the bedrock, primarily along fractures. Permeable glacial deposits range from extremely transmissive gravels to poorly sorted tills. Buried valleys, till, deltas, kames, and other glacial artifacts influence the transmission of ground water within the region. Two examples of localized flow are presented in Figure 10-9. The first example shows a flow regime in an area where till has the highest hydraulic conductivity relative to the other materials. In the second example, the till bed has a much lower hydraulic conductivity than the deltaic outwash deposited above it.

Thick regolith overlies fractured crystalline and metamorphic bedrock in most of the Piedment and Blue Ridge region. The hydraulic conductivities of regolith and fractured bedrock are similar. However, bedrock wells generally have much larger ground-water yields than regolith wells because, being deeper, they have available a much larger drawdown. Fracture-controlled movement of ground water through bedrock is illustrated in Figure 10-10, as is ground-water movement through saprolite (weathered bedrock) and river alluvium.

The Northeast and Superior Uplands region is characterized by folded and faulted igneous and metamorphic bedrock overlain by glacial deposits. The primary difference in the ground-water environment between this region and the Piedmont and Blue Ridge region is the presence of glacial material rather than regolith. The different types of glacial material have vastly different storage capacities and hydraulic conductivities. Examples of ground-water flow through till, delta, and kame deposits, as well as a generalized ground-water regime with upward gradients, are illustrated in Figure 10-11.

The Atlantic and Gulf Coastal Plain region is underlain by unconsolidated sediments that consist primarily of sand, silt, and clay. The sediments are often interbedded as a result of deposition on floodplains or deltas and subsequent reworking by ocean currents. Recharge to the ground-water system occurs in the interstream areas; most streams in this region are gaining streams. (See Figure 10-12.) Encroachment of salt water into well drawdown areas can be a problem in this area if high rates of ground-water withdrawal occur. An example (shown in Figure

10-12) of a flow net for a waste disposal site in New Jersey shows how regional flow may differ from the expected flow based on local topography. Also shown in Figure 10-12 is a proposed landfill site in an area of high recharge near the Savannah River in Georgia.

Ground water in the Southeast Coastal Plain region lies primarily within semiconsolidated limestone. Sand, gravel, clay, and shell beds overlie the limestone beds. Recharge in this region occurs by infiltration of precipitation directly into exposed limestone, and by seepage through the permeable soils that partly mantle the limestone. (See Figure 10-13.) Coastal environments such as beaches and bars and swamp areas have different ground-water regimes, shown in Figure 10-13. Flow through solution channels and large fractures in limestone is often rapid and thus the flow lines shown on the flow nets are highly idealized.

The geohydrologic setting for the Hawaiin Islands and Alaska Regions are provided in Figures 10-14 and 10-15, respectively.

Alluvial Valleys occur throughout the United States and can supply water to wells at moderate to high rates (See Figure 10-16). These valleys are underlain by sand and gravel deposited by streams carrying sediment-laden melt water from glaciation that occurred during the Pleistocene era. These valleys are considered a distinct ground-water terrain. These valleys have thick sand and gravel deposits that are in a clearly defined band and are in hydraulic contact with a perennial stream. The sand and gravel deposits generally have a transmissivity on the order of ten or more times greater than that of the adjacent bedrock. Silt and clay are commonly found both above and below the sand and gravel channels in the Alluvial Valley's as a result of overbank flooding of rivers. Ground-water recharge is predominantly by precipitation on the valleys, and also by ground water moving from the adjacent and underlying aquifers, by overbank flooding of the streams, and in some glacial valleys, by infiltration from tributary streams. An example of a flow net illustrating local ground-water movement beneath a waste disposal site in Connecticut is also shown in Figure 10-16.

In addition to determining the directions of ground-water flow, it is essential to determine the approximate rates of ground-water movement to properly design a monitoring program. Hydraulic conductivity, hydraulic gradient, and effective porosity data are required to estimate the average linear velocity of ground water and, therefore, assist in the determination of the rate of contaminant migration. Hydraulic conductivity data can be determined using single well (slug) test data. Several hydraulic conductivity measurements can be made on materials penetrated by individual wells to provide data on the relative heterogeneity of the materials in question. Measurements made in several wells also provide a comparison to check for effects of poor well construction. Hydraulic conductivity can also be determined from multiple-well (pumping) tests. A multiple-well test provides a hydraulic conductivity value for a larger portion of the aquifer. Hydraulic conductivities determined in the laboratory have been shown to vary by orders of magnitude from values determined by field methods and are, therefore, not recommended for use in the RFI.

Porosity can have an important controlling influence on hydraulic conductivity. Materials with high porosity values generally also have high hydraulic conductivities. An exception is clayey geologic materials which, although possessing high porosities, have low hydraulic conductivity values (resulting in low flow rates) due to their molecular structure. All of the pore spaces within geologic materials are not available for water or solute flow. Dead-end pores and the portion of the total porosity occupied by water held to soil particles by surface tension forces, do not contribute to effective porosity. Therefore, to determine average linear velocities, the effective porosity of the materials should be determined. In the absence of measured values, the values provided in Table 10-4 should be used.

Knowledge of the rates of ground-water flow is essential to determine if the locations of the monitoring wells are within reasonable flow distances of the contaminant sources. Flow rate data can also be used to calculate reasonable sampling frequencies. This is particularly important when attempting to monitor the potential migration of a intermittent contaminant release.

Geochemical and biological properties of the aquifer matrix should be evaluated in terms of their potential interference with the goals of the monitoring program. For example, chemical reactions or biological transformations of the monitoring constituents of concern may introduce artifacts into the results. Physical and hydrologic conditions will determine whether or not information on chemical

TABLE 10-4. DEFAULT VALUES FOR EFFECTIVE POROSITY

Soil Textural Classes	Effective Porosity of Saturation[a]
Unified Soil Classification System	
GC, GP, GM, GS SW, SP, SM, SC	0.20 (20%)
ML, MH	0.15 (15%)
CL, OL, CH, OH, PT	0.01 (1%)[b]
USDA Soil Textural Classes	
Clays, silty clays, sandy clays	0.01 (1%)[b]
Silts, silt loams, Silty clay loams	0.10 (10%)
All others	0.20 (20%)
Rock Units (all)	
Porous media (nonfractured rocks such as sandstone and some carbonates)	0.15 (15%)
Fractured rocks (most carbonates, shales, granites, etc.)	0.0001 (0.01%)

[a] These values are estimates. There may be differences between similar units.

[b] Assumes de minimus secondary porosity. If fractures or soil structure are present, effective porosity should be 0.001 (0.1%).

or biological interactions can be collected. If the potential for these reactions or transformations exists, consideration should be given to monitoring for likely intermediate transformation or degradation products.

The monitoring system design is influenced in many ways by a site's hydrogeologic setting. Determination of the items noted in the stratigraphy and flow systems discussions will aid in logical monitoring network configurations and sampling activities. For example:

- Background and downgradient wells should be screened in the same stratigraphic horizon(s) to obtain comparable ground-water quality data. Hydraulic conductivities should be determined to evaluate preferential flowpaths (which will require monitoring) and to establish sampling frequencies.

- The distances between and number of wells (well density) should be a function of the spatial heterogeneity of a site's hydrogeology, as is sampling frequency. For example, formations of unconsolidated deposits with numerous interbedded lenses of varying hydraulic conductivity or consolidated rock with numerous fracture traces will generally require a greater number of sampling locations to ensure that contaminant pathways are intercepted.

- The slope of the potentiometric surface and the slope of the aquitard formation strongly influence the migration rates of light and dense immiscible compounds.

- The hydrogeology will strongly influence the applicability of various geophysical methods (Appendix C), and should be used to establish boundary conditions for any modeling to be performed for the site.

- Analyses for contaminants of concern in the ground water monitoring program can be influenced by the general water quality present. Naturally-occurring cations and anions can affect contaminant reactivity, solubility, and mobility.

- Sites with complex geology will generally require more hydrogeologic information to provide a reasonable assurance that well placements will intercept contaminant migration pathways. For example, Figure 10-17 illustrates a cross-sectional and plan view of a waste landfill located in a mature Karst environment. This setting is characteristic of carbonate environments encountered in various parts of the country, but especially in the southeastern states. An assessment of the geology of the site through the use of borings, geophysical surveys, aerial photography, tracer studies, and other geological investigatory techniques, identified a mature Karst geologic formation characterized by well defined sinkholes, solution channels and extensive vertical and horizontal fracturing in an interbedded limestone/dolomite. Using potentiometric data, ground-water flow was found to be in an easterly direction.

  Solution channels are formed by the flow of water through the fractures. The chemical reaction between the carbonate rock and the ground-water flow in the fractures produces solution channels. Through time, these solution channels are enlarged to the point where the weight of the overlaying rock is too great to support; consequently causing a "roof" collapse and the formation of a sinkhole. The location of these solution channels dictate the placement of monitoring wells. Note that in Figure 10-17 the placement of well No. 2 is offset 50 feet from the perimeter of the landfill. The horizontal placement of well No. 2, although not immediately adjacent to the landfill, is necessary in order to monitor all potential contaminant pathways. The discrete nature of these solution channels dictate that each potential pathway be monitored.

  The height of the solution channels ranges from three to six feet directly beneath the sinkhole to one foot under the landfill. The vertical extent of the cavities allow for full screening of the horizontal solution channels. (Note the change in orientation of solution channels due to the presence of the fossil hash layer).

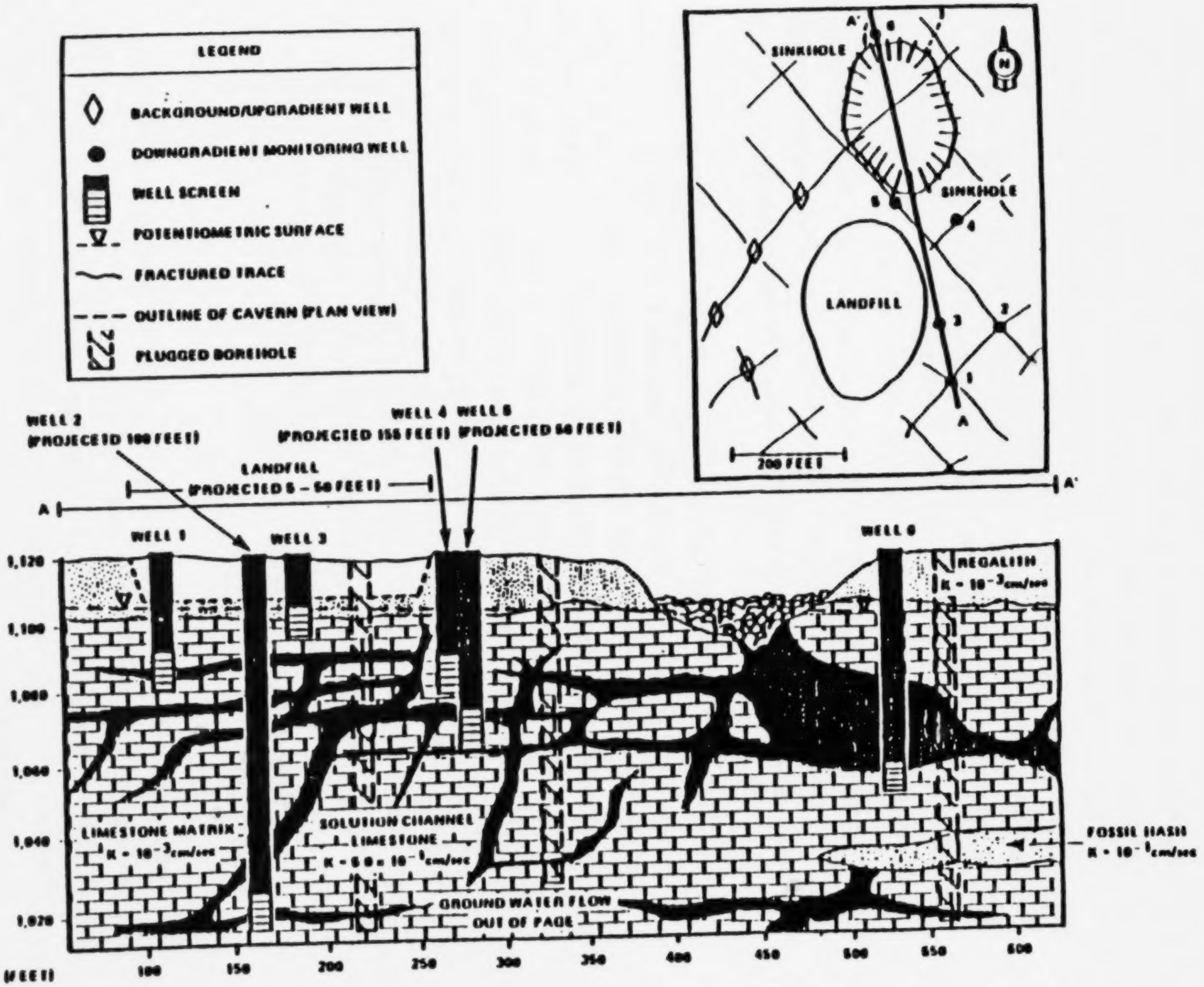

LEGEND
◊ BACKGROUND/UPGRADIENT WELL
● DOWNGRADIENT MONITORING WELL
WELL SCREEN
POTENTIOMETRIC SURFACE
FRACTURED TRACE
OUTLINE OF CAVERN (PLAN VIEW)
PLUGGED BOREHOLE
SINKHOLE
SINKHOLE
LANDFILL
A
A'
1
2
3
4
5
6
N
200 FEET
WELL 2
(PROJECETD 100 FEET)
LANDFILL
(PROJECTED 5 – 50 FEET)
WELL 4
(PROJECTED 155 FEET)
WELL 5
(PROJECTED 50 FEET)
A
A'
WELL 1
WELL 3
WELL 6
REGALITH
K = 10^-3 cm/sec
LIMESTONE MATRIX
K = 10^-3 cm/sec
SOLUTION CHANNEL
LIMESTONE
K = 5.0 x 10^-1 cm/sec
GROUND WATER FLOW
OUT OF PAGE
FOSSIL HASH
K = 10^-1 cm/sec
1,120
1,100
1,080
1,060
1,040
1,020
(FEET)
100
150
200
250
300
350
400
450
500
550
600

Figure 10-17. Monitoring well placement and screen lengths in a mature karst terrain/fractured bedrock setting.

Chapter I of the RCRA Ground Water Monitoring Technical Enforcement Guidance Document (TEGD) (U.S. EPA, 1986) provides additional guidance in characterization of site hydrogeology. Various sections of the document will be useful to the facility owner or operator in developing monitoring plans for RCRA Facility Investigations.

In order to further characterize a release to ground water, data should be collected to assess subsurface stratigraphy and ground-water flow systems. These are discussed in the following subsections.

10.3.3.1 Subsurface Geology

In order to adequately characterize the hydrologic setting of a site, an analysis of site geology should first be completed. Geologic site characterization consists of both a characterization of stratigraphy, which includes unconsolidated material analysis, bedrock features such as lithology and structure, and depositional information, which indicates the sequence of events which resulted in the present subsurface configuration.

Information that may be needed to characterize a site's subsurface geology includes:

- Grain size distribution and gradation;
- Hydraulic conductivity;
- Porosity;
- Discontinuities in soil strata; and
- Degree and orientation of subsurface stratification and bedding.

Refer to Section 9 (Soil) for further details.

Grain size distribution and gradation--A measurement of the percentage of sand, silt, and clay should be made for each distinct layer of the soil. Particle size can affect contaminant transport through its impact on adsorption and hydraulic conductivity. Sandy soils generally have low sorptive capacity while clays tend to have a high affinity for heavy metals and some organic contaminants. This is due in part to the fact that small clay particles have a greater surface area in relation to their volume than do large sand particles. Greater surface areas lead to stronger interactions with contaminant molecules. Clays also bind contaminants due to the chemical structure of the clay. Methods for determination of sand/silt/clay fractions are available from ASTM, Standard Method No. D422-63 (ASTM, 1984).

Hydraulic conductivity--This property represents the ease with which fluids can flow through a formation, and is dependent on porosity, and grain size, as well as on the viscosity of the fluid. Hydraulic conductivity can be determined by the use of field tests, as discussed in Section 10.6.

Porosity--Soil porosity is the volume percentage of the total volume of the soil not occupied by solid particles (i.e., the volume of the voids). In general, the greater the porosity, the more readily fluids may flow through the soil, with the exception of clays (high porosity), in which fluids are held tightly by capillary forces.

Discontinuities in geological materials--Folds are layers of rock or soil that have been naturally bent over geologic time. The size of a fold may vary from several inches wide to several miles wide. In any case, folding usually results in a complex structural configuration of layers (Billings, 1972).

Faults are ruptures in rock or soil formations along which the opposite walls of the formation have moved past each other. Like folds, faults vary in size. The result of faulting is the disruption of the continuity of structural layers.

Folds and faults may act as either barriers to or pathways for ground-water (and contaminant) flow. Consequently, complex hydrogeologic conditions may be exhibited. The existence of folds or faults can usually be determined by examining geologic maps or surveys. Aerial photographs can also be used to identify the existence of these features. Where more detailed information is needed, field methods (e.g., borings or geophysical methods) may need to be employed.

Joints are relatively smooth fractures found in bedrock. Joints may be as long as several hundred feet (Billings, 1972). Most joints are tight fractures, but because of weathering, joints may be enlarged to open fissures. Joints result in a secondary porosity in the bedrock which may be the major pathway of ground- water flow through the formation (Sowers, 1981).

Interconnected conduits between grains may form during rock formation (Sowers, 1981). The permeability of a bedrock mass is often defined by the degreeof jointing. Ground water may travel preferentially along joints, which usually governs the rate of flow through the bedrock. The degree and orientation of joints and interconnected voids is needed to determine if there will be any vertical or horizontal leakage through the formation. In some cases, bedrock acts as an aquitard, limiting the ground-water flow in an aquifer. In other cases, the bedrock may be much more productive than overlying alluvial aquifers.

Geologic maps available from the USGS (see Section 7) may be useful in obtaining information on the degree and orientation of jointing or interconnected void formation. Rock corings may also be used to identify these characteristics.

Degree and orientation of subsurface stratification and bedding--The owner or operator should develop maps of the subsurface structure for the areas of concern. These maps should identify the thickness and depth of formations, soil types and textures, the locations of saturated regions and other hydrogeological features. For example, the existence of an extensive, continuous, relatively horizontal, shallow strata of low permeability can provide a clue to contaminant routing. In such cases, the contaminants may migrate at shallow depths, which are above the regional aquifer. Such contamination could discharge into nearby, low-lying structures (e.g., seepage into residential basements). This basement seepage pathway has been demonstrated to be a significant migration channel in many cases. This pathway may result from migration of vapors in the vadose zone or through lateral migration of contaminated ground water. Basement seepage is more likely to occur in locations with shallow ground water.

A variety of direct and indirect methods are available to characterize a site geologically with respect to the above geologic characteristics. Direct methods utilize soil borings and rock core samples and subsequent lab analysis to evaluate grain size, texture, uniformity, mineralogy, soil moisture content, bedrock lithology, porosity, and structure. Combined, these data provide the basis for delineating the geologic nature of the site and, in turn, provide the data necessary to evaluate the hydrologic setting.

Indirect methods of geologic investigation, such as geophysical techniques (See Appendix C) and aerial photography (See Appendix A) can be used to supplement data gathered by direct field methods, through extrapolation and correlation of data on surface and subsurface geologic features. Borehole geophysical techniques can be used to extrapolate direct data from soil borings and bedrock cores. Surface geophysical methods can provide indirect information on depth, thickness, lateral extent, and variation of subsurface features that can be used to extrapolate information gained from direct methods. Applicable surface geophysical methods include seismic refraction, electrical resistivity, electromagnetics, magnetics, and ground penetrating radar.

10.3.3.2 Flow Systems

In addition to characterizing the subsurface geology, the owner or operator should adequately describe the ground-water flow system. To adequately describe the ground-water flow paths, the owner or operator should:

- Establish the direction of ground-water flow (including horizontal and vertical components of flow);

- Establish the seasonal, temporal, and artificially induced (e.g., offsite production well pumping, agricultural use) variations in ground-water flow; and

- Determine the hydraulic conductivities of the hydrogeologic units underlying the site.

Hydrologic and hydraulic properties and other relevant information needed to fully evaluate the ground-water flow system are listed and discussed below:

- Hydraulic conductivity;

- Hydraulic gradient (vertical and horizontal);
- Direction and rate of flow;
- Aquifer type/identification of aquifer boundaries;
- Specific yield (effective porosity)/storage coefficient;
- Depth to ground water;
- Identify uppermost aquifer;
- Identify recharge and discharge areas;
- Use of aquifer; and
- Aquitard type and location.

Hydraulic conductivity--In addition to defining the direction of ground-water flow in the vertical and horizontal directions, the owner or operator should identify the distribution of hydraulic conductivity within each formation. Variations in the hydraulic conductivity of subsurface materials can affect flow rates and alter directions of ground-water flow paths. Areas of high hydraulic conductivity represent areas of greater ground-water flow and zones of potential migration. Therefore, information on hydraulic conductivities is needed to make decisions regarding well placements. Hydraulic conductivity measurement is described in Section 10.6.

Hydraulic gradient--The hydraulic gradient is defined as the change in static head per unit distance in a given direction. The hydraulic gradient defines the direction of flow and may be expressed on maps of water level measurements taken around the site. Ground-water velocity is directly related to hydraulic gradient. Both vertical and horizontal gradients should be characterized.

Direction and rate of flow--A thorough understanding of how ground water flows beneath the facility will aid the owner or operator in locating wells to provide suitable background and/or downgradient samples. Of particular importance is the direction of ground-water flow and the impact that external factors (intermittent well pumping, temporal variations in recharge patterns, tidal effects, etc.) may have on ground-water flow patterns. In order to account for these factors, monitoring procedures should include precise water level measurements in piezometers or observation wells. These measurements should be made in a sufficient number of wells and at a frequency sufficient to adequately gauge both seasonal average flow directions and to show any seasonal or temporal fluctuations in flow directions. Horizontal and vertical components of ground-water flow should be assessed. Methods for determining vertical and horizontal components of flow are described in Subsection 10.5.4.

Identification of aquifer boundaries/aquifer type--Aquifer boundaries define the flow limits and the degree of confinement of an aquifer. There are two major types of aquifers: unconfined and confined. An unconfined aquifer has a free water surface at which the fluid pressure is the same as atmospheric. A confined aquifer is enclosed by retarding geologic formations and is, therefore, under pressure greater than atmospheric. A confining unit consists of consolidated or unconsolidated earth materials that are substantially less permeable than aquifers. Confining units are called aquitards or aquicludes. Aquifer boundaries can be identified by consulting geologic maps and state geologic surveys. Observation wells and piezometers can be used to determine the degree of confinement of an aquifer through analysis of water level data.

Specific yield/storativity--Specific yield and storativity are both terms used to characterize the amount of water an aquifer is capable of yielding. In an unconfined system, the specific yield is the ratio of the drainable volume to the bulk volume of the aquifer medium (some liquid will be retained in pore spaces). The storativity of a confined aquifer is the volume of water released from a column of unit area and height per unit decline of pressure head. Specific yield or storativity values may be necessary to perform complex ground-water modeling.

Depth to ground water--The depth to ground water is the vertical distance from the land's surface to the top of the saturated zone. A release from a unit not in contact with the water table will first percolate through the unsaturated zone and may, depending upon the nature of the geologic material, disperse horizontally. Thus, a release of this nature may reach a deep water table with some lateral spreading. Depth to ground water can influence the selection of sampling methods as well as geophysical methods.

A shallow water table can also facilitate releases to other environments via volatilization of some compounds into the unsaturated zone, seepage into basements of buildings in contact with the saturated zone, or the transport of contaminants into wetlands where the water table reaches the level of the ground surface. Sufficient mapping of the water table with particular attention to these features should provide an indication of where these interactions may exist.

Identification of uppermost aquifer--As defined in 40 CRF §260.10, "aquifer" means a geologic formation, group of formations, or part of a formation capable of yielding a significant amount of ground water to wells or springs. "Uppermost aquifer," also defined in 40 CRF §260.10, means the geologic formation nearest the natural ground surface that is an aquifer, as well as lower aquifers that are hydraulically interconnected with this aquifer within the facilitiy's property boundary. Chapter one of the Technical Enforcement Guidance Document (TEGD) (U.S. EPA, 1986) elaborates on the uppermost aquifer definition. It states that the identification of the confining layer or lower boundary is an essential facet of the definition. There should be very limited interconnection, based on pumping tests, between the uppermost and lower aquifers. If zones of saturation capable of yielding significant amounts of water are interconnected, they all comprise the uppermost aquifer. Identification of formations capable of "significant yield" must be made on a case-by-case basis.

There are saturated zones, such as low permeability clay, that may not yield a significant amount of water, yet may act as pathways for contamination that can migrate horizontally for some distance before reaching a zone which yields a significant amount of water. In other cases, there may be low yielding saturated zones above the aquifer which can provide a pathway for contaminated ground water to reach basements. If there is reason to believe that a potential exists for contamination to escape along such pathways, the owner or operator should monitor such zones.

For further information on the suppermost aquifer definition, including examples illustrating the determination of hydraulic interconnection in various geologic settings, see Chapter One of the TEGD.

Identification of recharge and discharge areas--Ground-water recharge can be defined as the entry into the saturated zone of water made available at the water table surface, together with the associated flow away from the water table within the saturated zone. Ground-water discharge can be defined as the removal of water from the saturated zone across the water table surface, together with the associated flow toward the water table within the saturated zone (Freeze and Cherry, 1979). Ground-water recharge and discharge areas also represent areas of potential inter-media transport.

Recharge can be derived from the infiltration of precipitation, inter-aquifer leakage, inflow from streams or lakes, or inadvertently by leakage from lagoons, sewer lines, landfills, etc. Discharge occurs where ground water flows to springs, streams, swamps, or lakes, or is removed by evapotranspiration or pumping wells, etc. Information on the source and location of aquifer recharge and discharge areas may be obtained from state water resource publications, geologic surveys, or existing site information. Comparison of aquifer water levels with nearby surface water levels may also provide an indication of the source and location of aquifer recharge and discharge areas.

Flow nets can also be used to determine areas of aquifer recharge and discharge. Section 10.5.2 describes the use of flow nets to determine ground-water flow patterns.

Use of aquifer--The proximity and extent of local ground-water use (e.g., pumping) may dramatically influence the rate and direction of ground-water flow possibly causing seasonal or episodic variations. These factors should be considered when designing and implementing a ground-water monitoring system. Information on local aquifer use may be available from the USGS, and state and local water authorities. Aquifer use for drinking water or other purposes may also influence the location of ground-water monitoring wells, as it may be appropriate to monitor at locations pertinent to receptors.

Aquitard type and location--Aquitard type refers to the type of geologic formation that serves to bound ground-water flow for a given aquifer. Such boundaries may be rock or may be an unconsolidated unit such as clay, shale, or glacial till. The identification of such formations and their hydraulic characteristics is essential in determining ground-water flow paths. Aquitard locations can be determined by consulting geologic maps and boring log information. Although aquitards are substantially less permeable than aquifers, they are not totally impermeable and can allow significant quantities of water to pass through them over time. The location of an aquitard should be used in determining monitoring well depths.

10.3.4 Sources of Existing Information

A complete review of relevant existing information on the facility is an essential part of the release characterization. This review can provide valuable knowledge and a basis for developing monitoring procedures. Information that may be available and useful for the investigation includes both site-specific studies and regional surveys available from local, state, and Federal agencies.

Information from the regulatory agency such as the RFA report should be thoroughly reviewed in developing monitoring procedures, and should serve as a primary information source. It may also provide references to other sources of information. In addition, the facility's RCRA Permit Application may contain other relevant information. These reports and all of the facility's RCRA compliance/permit files will provide an understanding of the current level of knowledge about the facility, and will assist in identifying data gaps to be filled during the investigation.

Public information is available from local, state, and Federal governments (see Section 7) concerning the topics discussed below.

10.3.4.1 Geology

Knowledge of local bedrock types and depths is important to the investigation of a site. Sources of geologic information include United States Geological Survey

(USGS) reports, maps, and files; State geological survey records; and local well drilling logs. See also Section 9 (Soils).

10.3.4.2 Climate

Climate is also an important factor affecting the potential for contaminant migration from a release source. Mean values for precipitation, evaporation, evapotranspiration, and estimated percolation will help determine the potential for onsite and offsite contaminant transport. The investigator should consult monthly or seasonal precipitation and evaporation (or temperature) records. Climate and weather information can be obtained from:

National Climatic Center
Department of Commerce
Federal Building
Asheville, North Carolina 28801
Tel: (704)258-2850

10.3.4.3 Ground-Water Hydrology

The owner or operator will need to acquire information on the ground-water hydrology of a site and its surrounding environment. Ground-water use in the area of the site should be thoroughly investigated to find the depths of local wells, and their pumping rates. Sources of such information include the USGS, state geological surveys, local well drillers, and State and local water resources boards. A list of all state and local cooperating offices is available from the USGS, Water Resources Division in Reston, Virginia, 22092. This list has also been distributed to EPA Regional Offices. Water quality data, including surface waters, is available through the USGS via their automated NAWDEX system. For further information, telephone (703)860-6031.

10.3.4.4 Aerial Photographs

Aerial reconnaissance can be an effective and economical tool for gathering information on waste management facilities. For this application, aerial reconnaissance includes aerial photography and thermal infrared scanning. See

Appendix A for a detailed discussion of the usefulness of aerial photography in release characterization and availability of aerial photographs.

10.3.4.5 Other Sources

Other sources of information for subsurface and release characterization include:

- U.S. EPA files (e.g., CERCLA-related reports);
- U.S. Geological Survey;
- U.S. Department of Agriculture Soil Conservation Service;
- U.S. Department of Agriculture Agricultural Stabilization and Conservation Service;
- U.S. Department of Interior -Bureau of Reclamation;
- State Environmental Protection or Public Health Agencies;
- State Geological Survey;
- Local Planning Boards;
- County or City Health Departments;
- Local Library;
- Local Well Drillers; and
- Regional Geologic and Hydrologic Publications.

10.4 Design of a Monitoring Program to Characterize Releases

Information on waste, unit and environmental characterization can be used to develop a conceptual model of the release, which can subsequently be used to design a monitoring program to fully characterize the release. The design of a monitoring program is discussed below.

10.4.1 Objectives of the Monitoring Program

The objective of initial monitoring is to verify or to begin characterizing known or suspected contaminant releases to ground water. To help accomplish this objective, the owner or operator should evaluate any existing monitoring wells to determine if they are capable of providing samples representative of background and downgradient ground-water quality for the unit(s) of concern. Figure 10-18

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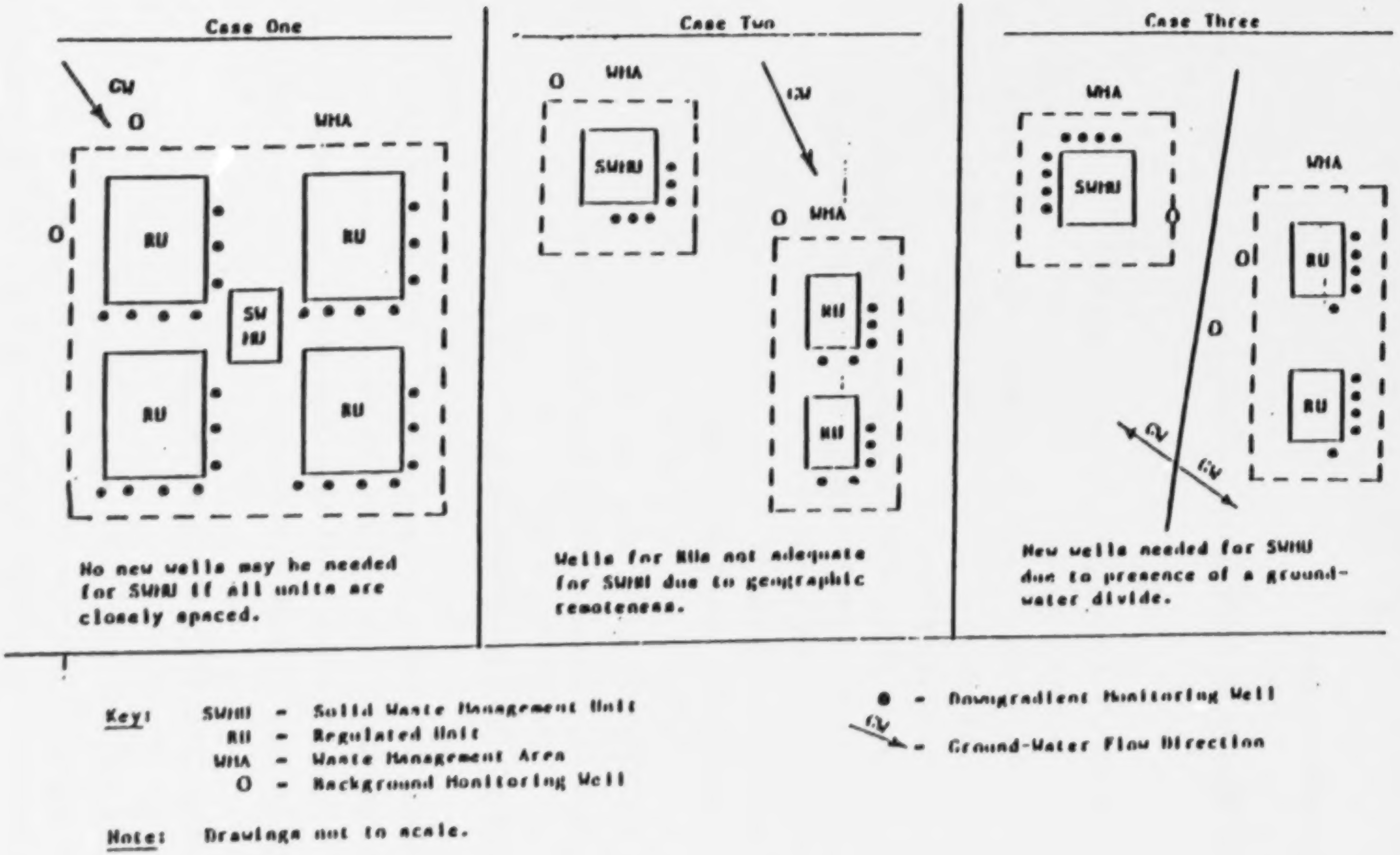

Case One
GW
O
WMA
RU
SW MU
No new wells may be needed for SWMU if all units are closely spaced.
Case Two
O
WMA
SWMU
GW
RU
Wells for RUs not adequate for SWMU due to geographic remoteness.
Case Three
WMA
SWMU
GW
RU
New wells needed for SWMU due to presence of a ground-water divide.
Key: SWMU - Solid Waste Management Unit
RU - Regulated Unit
WMA - Waste Management Area
O - Background Monitoring Well
● - Downgradient Monitoring Well
GW - Ground-Water Flow Direction
Note: Drawings not to scale.

Figure 10-18.
Monitoring well locations

illustrates three cases where existing well systems are evaluated with regard to their horizontal location for use in a ground-water investigation. Adequacy is not only a function of well location but also well construction. Guidance on appropriate well construction materials and methods can be found in the TEGD (EPA, 1986). If the monitoring network is found to be inadequate for all or some of the units of concern, additional monitoring wells should be installed. Further characterization, utilizing both direct and indirect investigative methods, of the site's hydrogeology should be completed to identify appropriate locations for the new monitoring wells.

If initial monitoring verifies a suspected contaminant release, the owner or operator should extend the monitoring program to determine the vertical and horizontal concentrations (e.g., 3- dimensions) of all hazardous constituents in the release. The rate of contaminant migration should also be determined. A variety of investigatory techniques are available for such monitoring programs.

Monitoring procedures should include direct methods of obtaining ground-water quality information (e.g., sampling and analysis of ground water from monitoring wells). Indirect methods of investigation may be used when appropriate to aid in determining locations for monitoring wells (i.e., through geologic and/or geochemical interpretation of indirect data). For many cases, the use of both direct and indirect methods may be the most efficient approach.

Elements to be addressed in the ground-water monitoring program include:

- Indicator parameters and constituents to be monitored;
- Frequency and duration at which samples will be taken;
- Sampling and analysis techniques to be used, including appropriate QA/QA procedures; and
- Monitoring locations.

[Note: Permit application regulations in 40 CFR §270.14(c)(2) require applicants to identify the uppermost aquifer and hydraulically interconnected aquifers beneath the facility property if the facility has any "regulated" units. The application must indicate ground-water flow directions and provide the basis for the aquifer identification (e.g., a report written by a qualified hydrogeologist on the hydrogeologic characteristics of the facility property supported by at least the well drilling logs and available professional literature). However, some RCRA permit applications did not require hydrogeologic characterizations (e.g., storage only facilities) prior to the HSWA Amendments of 1984. Now, such characterizations may be required according to RCRA Section 3004(u) when SWMU releases to ground water are suspected or known. The RCRA Ground Water Monitoring Technical Enforcement Guidance Document (TEGD) (U.S. EPA, 1986), and the Permit Applicant's Guidance Manual for Hazardous Waste Land Treatment, Storage, and Disposal Facilities (U.S. EPA, 1984) should be consulted for further information on regulatory requirements.]

10.4.2 Monitoring Constituents and Indicator Parameters

Initial monitoring should be focused on rapid, effective release characterization at the downgradient limit of the waste management area. Monitoring constituents should include waste-specific subsets of hazardous constituents from 40 CFR Part 261, Appendix VIII (see Section 3 and the lists provided in Appendix B). Indicator parameters (e.g., TOX, specific conductance) may also be proposed as indicated in Section 3. Such indicators alone may not be sufficient to characterize a release of hazardous constituents, since the natural background variability of indicator constituents can be quite high. Furthermore, indicator concentrations do not precisely represent hazardous constituent concentrations, and the detection limits for indicator analyses are significantly higher than those for specific constituents.

In developing an initial list of monitoring constituents and indicator parameters, the following items should be considered:

- The nature of the wastes managed at the facility should be reviewed to determine which constituents (and any chemical reaction products, if appropriate) are relatively mobile and persistent;

- The effects of the unsaturated zone (if present) beneath the facility on the mobility, stability and persistence of the waste constituents; and

- The concentrations and related variability of the proposed constituents in background ground water.

In the absence of detailed waste characterization information, the owner or operator should review the guidance presented in Section 3, which discusses the use of the monitoring constituent lists in Appendix B. As discussed in Section 3, the use of these lists is contingent upon the level of detail provided by the waste characterization.

The owner or operator should consider monitoring for additional inorganic indicators that characterize the general quality of water at the site (e.g., chloride, iron, manganese, sodium, sulfate, calcium, magnesium, potassium, nitrate, phosphate, silicate, ammonium, alkalinity and pH). Baseline data on such indicators can be used for subsequent monitoring phases and in eventually selecting corrective measures. This is also discussed in Section 3 and Appendix B. For example, information on the major anions and cations that make up the bulk of dissolved solids in water can be used to determine reactivity and solubility of hazardous constituents and therefore predict their mobility under actual site conditions.

10.4.3 Monitoring Schedule

10.4.3.1 Monitoring Frequency

Monitoring frequency should be based on various factors, including:

- Ground-water flow rate and flow patterns;

- Adequacy of existing monitoring data; and

- Climatological characteristics (e.g., precipitation patterns).

Generally, the greater the rate of ground-water flow, the greater the monitoring frequency needed. For example, monitoring frequency in an intergranular porosity flow aquifer of low permeability materials would likely be less than for a fracture or solution porosity flow aquifer with unpredictable and high flow rates. In the case of a fracture or solution porosity flow aquifer, it is possible that contaminants could migrate past the facility boundary in a matter of days, weeks, or months; thus requiring frequent monitoring.

The adequacy of existing monitoring data can be a factor in determining the monitoring schedule. For example, a facility which has performed adequate monitoring under interim status requirements may have a good data base which can be helpful in evaluating initial monitoring results. At the other end of the spectrum are facilities lacking hydrogeologic data and monitoring systems. Owners or operators of these facilities will need to design and install an adequate monitoring system for the units of concern. An accelerated monitoring program is recommended at such facilities.

10.4.3.2 Duration of Monitoring

The duration of the initial monitoring phase will vary with facility-specific conditions (e.g., hydrogeology, wastes present) and should be determined through consultation with the regulatory agency. The regulatory agency may evaluate initial monitoring results to determine how long monitoring should continue and to determine the need for adjustments in the monitoring schedule, the list of monitoring constituents, and other aspects of the monitoring effort. If the regulatory agency determines that a release to ground water has not occurred, the investigation process for that release can be terminated at its discretion. If contamination is found during initial monitoring, further monitoring to fully characterize the release will generally be necessary.

10.5.2 Environmental Setting Characterization

Environmental characteristics should be presented as follows:

- Tabular summaries of annual and monthly or seasonal relevant climatic inforamtion (e.g., temperature, precipitation);
- Narratives and maps of soil and relevant hydrogeological characteristics such as porosity, organic matter content and depth to ground water;
- Maps showing location of natural or man-made engineering barriers and likely migration routes; and
- Maps of geologic material at the site identifying the thickness, depth, and textures of soils, and the presence of saturated regions and other hydrogeological features.

Flow nets should be particularly useful for presenting environmental setting information for the ground-water medium. A flow net provides a graphical technique for obtaining solutions to steady state ground-water flow. A properly constructed flow net can be used to determine the distribution of heads, discharges, areas of high (or low) velocities, and the general flow pattern (McWhorter and Sunada, 1977).

The Ground Water Flow Net/Flow Line Technical Resource Document (TRD), NTIS PB86-224979. (U. S. EPA, 1985), provides detailed discussion and guidance in the construction of flow nets. Although the focus of this document is on the construction of vertical flow nets, the same data requirements and theoretical assumptions apply to horizontal flow nets. The fundamental difference between vertical and horizontal flow nets is in their application. A flow net in the horizontal plane may be used to identify suitable locations for monitoring wells whereas a flow net in the vertical plane would aid in determining the screened interval of a well.

The following excerpts from the Flow Net Document (U.S. EPA, 1985) explain data needs for flow net construction. Several assumptions must be made to construct a flow net:

- Ground-water flow is steady state, which means flow is constant with time;
- The aquifer is completely saturated;
- No consolidation or expansion of the soil or water occurs;
- The same amount of recharge occurs across the system; and
- Flow is laminar and Darcy's Law is valid.

Knowledge of the hydrologic parameters of the ground-water system is required to properly construct a flow net. These parameters include:

- Head distribution, both horizontally and vertically;
- Hydraulic conductivity of the saturated zone;
- Saturated zone thickness; and
- Boundary conditions.

The distribution of head can be determined using time equivalent water level measurements obtained from piezometers and/or wells. Plotting the water level elevations on a base map and contouring these data will provide a potentiometric surface. Contour lines representing equal head are called lines of equipotential. Changes in hydraulic head, both horizontally and vertically within an aquifer, must be known for proper flow-net construction. These changes can be delineated with piezometers or monitoring wells installed at varying depths and spatially distributed. The data must be time equivalent since water levels change over time. Ground-water flow directions can be determined by drawing lines perpendicular to the equipotential lines. Ground water flows from areas of high hydraulic head to areas of low hydraulic head.

The hydraulic conductivity of a material depends on the properties of the fluid and the media. Clayey materials generally have low hydraulic conductivities, whereas sands and gravels have high conductivities (U.S. EPA, 1985). Where flow crosses a boundary between different homogeneous media the ground-water flowlines refract and flow velocity changes due to an abrupt change in hydraulic conductivity. The higher permeability formation serves as a conduit to ground-water flow. This is visually apparent in a properly constructed flow net, since flow tubes are narrower in layers with higher conductivity because less area is necessary to conduct the same volume of ground water. In media of lower conductivity, flow tubes will be wider in order to conduct the same volume of flow (Cedergren, 1977). Construction of flow nets for layered geologic settings (heterogeneous, isotropic systems) are discussed in Section 2 of the flow net document (U.S. EPA, 1985).

The boundary conditions of an aquifer must also be known to properly construct a flow net. These boundary conditions will establish the boundaries of the flow net. The three types of boundaries are: 1) impermeable boundaries; 2) constant head boundaries; and 3) water table boundaries (Freeze and Cherry, 1979). Ground water will not flow across an impermeable boundary; it flows parallel to these boundaries. A boundary where the hydraulic head is constant is termed a constant head boundary. Ground-water flow at a constant head boundary is perpendicular to the boundary. Examples of constant head boundaries are lakes, streams, and ponds. The water table boundary is the upper boundary of an unconfined aquifer, and is a line of known and variable head. Flow can be at any angle in relation to the water table due to recharge and the regional ground-water gradient. The boundary conditions of an aquifer can be determined after a review of the geohydrologic data for a site (U.S. EPA, 1985).

Although a complete understanding of the mathematics of ground-water flow is not necessary for proper flow-net construction by graphical methods, a general understanding of the theory of ground-water flow is required. For a brief discussion of ground-water flow theory as applied to flow nets, refer to Section 1 of the flow net document (U.S. EPA, 1985). Detailed guidance on graphical construction of flow nets is given in Section 2 of that document. Mathematical techniques can be used to construct flow nets although graphical techniques are the simplest and most commonly used. It is worth noting that flow nets are dimensionless.

When a flow net has been constructed for a site, it may be possible to test the adequacy of the flow net by installing additional piezometers at selected locations. If the site hydrogeology is adequately characterized by the flow net, the head values in the new piezometer(s) will not vary significantly from those predicted by the flow net.

The number of new piezometers needed to check the adequacy of the flow net would vary depending on a number of factors including size of the site, complexity of the site hydrogeology, amount of data used to construct the flow net, and the level of agreement between the site specific flow net and the regional flow regime. For example, at a site with predominantly horizontal flow and well defined stratigraphy, such as illustrated in Figure 10-22, a single new piezometer could test the flow net. For a site with multiple, interconnected aquifers and a significant vertical component of flow, such as illustrated in Figure 10-23, several nested piezometers might be necessary to test the flow net.

In evaluating flow nets and the results of flow net tests, several factors should be kept in mind. The head measurements in a new piezometer may not exactly match the values predicted by the flow net. Some variation is inherent in this type of measurement. The owner or operator should evaluate whether or not the difference between measured and predicted values is significant in the context of flow direction or flow velocity. A new value which reverses the direction of flow or redirects flow towards potential receptors would obviously be significant. A change in flow velocity as indicated by a revised gradient might be significant if the magnitude of the change is substantial or if an increased velocity suggests that the characterization needs to be extended to a greater distance.

There are several situations in which extreme caution is needed in evaluating a flow net test. In many cases, temporal variations will alter the potentiometric surface between the time the flow net is constructed and a test piezometer is installed. Examples of this situation would include locations with large seasonal variations in ground-water levels. Another situation that would introduce problems

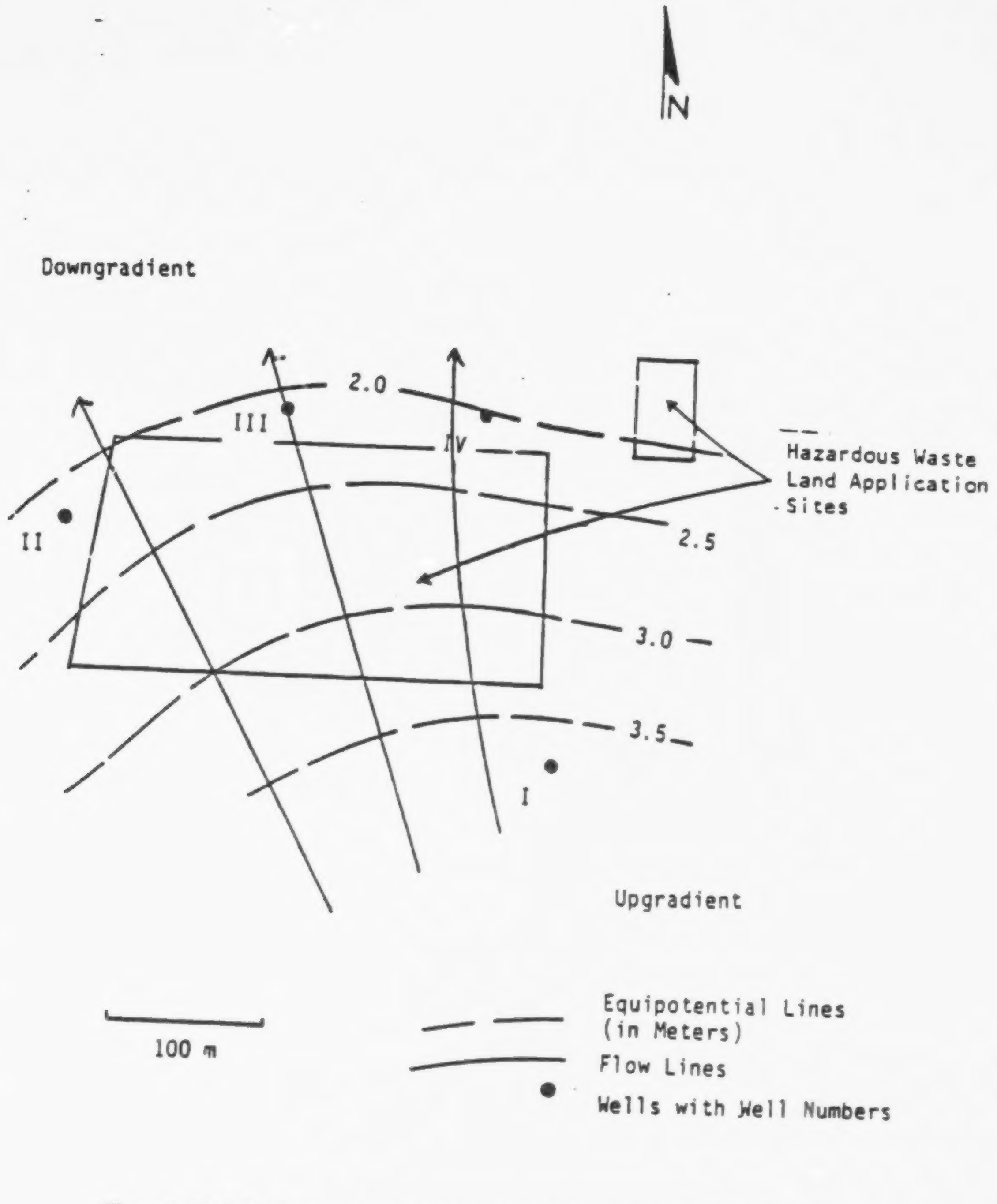
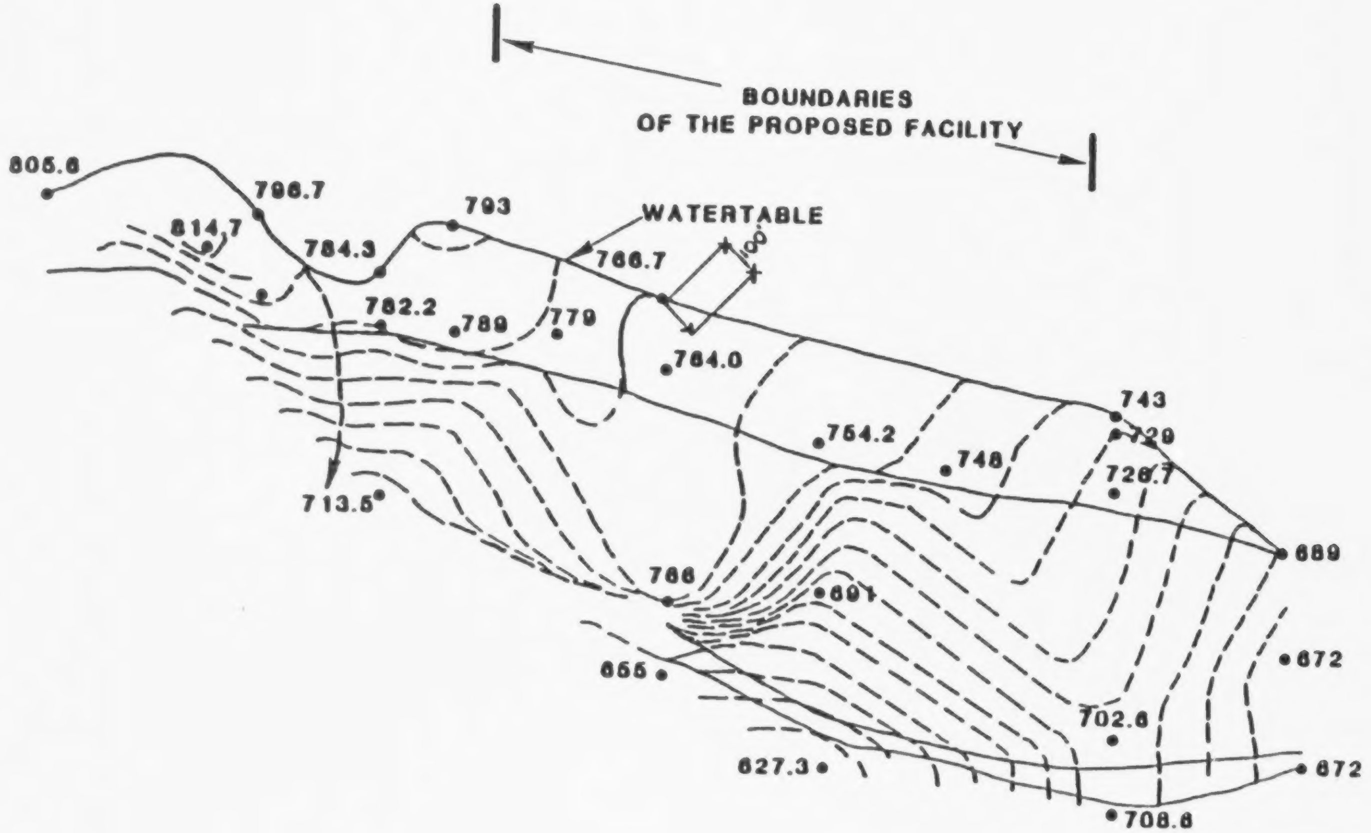

N
Downgradient
2.0
III
IV
II
2.5
3.0
3.5
I
Hazardous Waste Land Application Sites
Upgradient
100 m
Equipotential Lines (in Meters)
Flow Lines
Wells with Well Numbers

Figure 10-22. Potentiometric surface showing flow direction


BOUNDARIES
OF THE PROPOSED FACILITY
WATERTABLE
805.6
796.7
814.7
784.3
793
782.2
789
779
766.7
764.0
754.2
748
743
729
726.7
689
713.5
766
691
655
627.3
702.6
672
672
708.6

ASSUME 100 = $\frac{k_H}{k_v}$

Figure 10-23. Approximate flow net

in interpretation would be a site that is adjacent to tidally influenced surface waters.

Construction of flow nets is not appropriate or valid in certain instances. As discussed in the flow net document (U.S. EPA, 1985), these situations occur when there is a lack of three-dimensional hydrologic data for a ground-water system, and when ground- water flow in a system does not conform to the principles expressed by and assumptions made in Darcy's Law. Scaling problems occur when the aquifer and/or geologic layers associated with a particular ground-water system are thin in relation to the length of the flow net. If a flow net is constructed for this situation, the flow net will be made up of squares that are too small to work with unless the scale is exaggerated. For sites where the assumption of steady-state flow is not valid, the construction of flow nets is very difficult. The flow net must be redrawn each time the flow field changes to simulate the transient conditions.

Lack of three-dimensional hydrologic data or hydrologically equivalent data for a ground-water flow system makes proper flow-net construction impossible. Hydrologic testing at various depths within an aquifer and determination of the vertical hydraulic conductivity of an aquifer are essential to provide the necessary data. If these data are not available it will be necessary to obtain them before a flow net can be constructed.

There are three types of ground-water systems in which the principles expressed by Darcy's Law do not apply. The first is a system in which the flow is through materials with low hydraulic conductivities under extremely low gradients (Freeze and Cherry, 1979). The second is a system in which a large amount of flow passes through materials with very high hydraulic conductivities. The third is a system in which the porous media assumption is not valid. Darcy's Law expresses linear relationships and requires that flow be laminar (flow in which stream lines remain distinct from one another). In a system with high hydraulic conductivity, flow is often turbulent. Turbulent flow is characteristic of karstic limestone and dolomite, cavernous volcanics, and fractured rock systems. Construction of flow nets for areas of turbulent flow would not be valid. The use of Darcy's Law also requires the assumption of porous media flow. This assumption may not be valid for many fractured bedrock and karst environments where fractured flow is dominant or large solution features are present.

10.5.3 Characterization of the Release

The objective of monitoring is to estimate the nature, rate, and extent (3-Dimensional) of the release. Data are, therefore, collected from a set of monitoring wells that will allow characterization of the dimensions and concentrations of constituents in the plume, as well as the rate of flow.

Subsequent monitoring phases will often include the measurement of many more constituents in a more extensive well network than initial monitoring. This will often necessitate the collection of large amounts of data. Sections 6.8 and 6.9 of the TEGD (U.S. EPA, 1986) provide useful guidance on organizing, evaluating, and presenting monitoring data. Section 4.7 of TEGD addresses evaluation of the quality of ground-water data. Specific data presentation and evaluation procedures are presented below.

Migration rates can be determined by using the concentration of monitoring constituents over a period of time in wells aligned in the direction of flow. If these wells are located both at the edge of the release and in the interior of the release, subsequent analysis of the monitoring data can then provide an estimate of the rate of migration both of the contaminant front as a whole and of individual constituents within the release. This approach does not necessarily provide a reliable determination of the migration rates that will occur as the contaminant release moves further away from the facility, due to potential changes in geohydrologic conditions or degradation of the contaminants. More importantly, this approach requires the collection of a time series of data of sufficient duration and frequency to gauge the movement of contaminants. Such a delay is normally inappropriate during initial characterization of ground-water contamination since a relatively quick determination of at least an estimate of migration rates is needed to deduce the impact of ground-water contamination and to formulate an appropriate reaction.

Rapid estimates of migration rates should be made from aquifer properties obtained during the hydrogeologic investigation. The average linear velocity (v) of the ground water should be calculated using the following form of Darcy's Law:

$$\overline{v} = \frac{-Ki}{n_e}$$

where (K) is hydraulic conductivity, (i) is hydraulic gradient, and (n_e) is effective porosity. This assumes that contaminants flow at the same rate as ground water. This equation can be used to roughly estimate the rate of migration, both of the contaminant front as a whole, and of individual dissolved constituents within the release.

Rough estimates of migration rates beyond the facility property boundary can be made based on aquifer properties obtained during the site hydrogeologic characterization and knowledge of the physical and chemical properties of contaminants known to be present. By recognizing the various factors which can affect the transport of monitoring constituents, the owner or operator can determine approximate migration rates. Continued monitoring of the release over time should be conducted to verify the rate(s) of migration. Information on rate(s) of migration should be used in determining any additional monitoring well locations.

More refined estimates of contaminant migration rates should consider potential differential transport rates among various monitoring constituents. Differential transport rates are caused by several factors, including:

- Dispersion due to diffusion and mechanical mixing;
- Retardation due to adsorption and electrostatic interactions; and
- Transformation due to physical, chemical, and/or biological processes.

Dispersion results in the overall dilution of the contaminant; however, chromatographic separation of the contaminant constituents and differential dispersion effects can result in a contaminant arriving at a particular location before the arrival time computed solely on the average linear velocity of ground- water flow. Alternately, retardation processes can delay the arrival of contaminants beyond that calculated using average ground-water flow rate(s). Transformation of waste constituents is a complex process which can be difficult to estimate. While some contaminants, such as radionuclides, decay at a constant rate over time, most degradeable chemicals are influenced by a variety of factors and the interactions of these factors are difficult or impossible to predict. Local geologic variations will also affect constituent migration rates. Relating constituent migration rates to ground-water flow rates is a reasonable and relatively quick way to estimate contaminant flow rates. Where possible, contaminant- specific migration rates should also be determined.

Procedures for the evaluation of monitoring data vary in a site-specific manner, but should all result in determinations of the rate of migration, extent, and composition of hazardous constituents of the release. Where the release is obvious and/or chemically simple, it may be possible to characterize it readily from a descriptive presentation of concentrations found in monitoring wells and through geophysical measurements. Where contamination is less obvious or the release is chemically complex, however, the owner or operator may employ a statistical inference approach. The owner or operator should plan initially to take a descriptive approach to data analysis in order to broadly delineate the extent of contamination. Statistical comparisons of monitoring data among wells and/or over time may be necessary, should the descriptive approach provide no clear determination of the rate of migration, extent, and hazardous constituent composition of the release.

10.6 Field Methods

10.6.1 Geophysical Techniques

During the past decade, extensive development of remote sensing geophysical equipment, portable field instrumentation, field methods, analytical techniques and related computer processing have resulted in an improvement in the capability to characterize hydrogeology and contaminant releases. Some of these geophysical methods offer a means of detecting contaminant plumes and flow directions in both the saturated and unsaturated zones. Others offer a way to obtain detailed information about subsurface soil and rock characteristics. This capability to rapidly analyze subsurface conditions without disturbing the site offers the benefit of low cost and risk, and provides better overall understanding of complex site conditions.

Various geophysical techniques, including electromagnetic, seismic refraction, resistivity, ground penetrating radar, magnetic, and several borehole methods, are applicable to RCRA Facility Investigations. Table 10-6 suggests appropriate applications for the various geophysical tools. Appendix C provides additional information.

10.6.2 Soil Boring and Monitoring Well Installation

10.6.2.1 Soil Borings

Soil borings should be sufficient to characterize the subsurface geology below the site. Section 1.2 of TEGD (U.S. EPA, 1986) provides criteria for adequate borings. A summary of these criteria is presented below.

- Installation of initial boreholes at a density based on criteria described in Table 10-7 and sufficient to provide initial information upon which to determine the scope of a more detailed evaluation of geology and potential pathways of contaminant migration.

- Initial boreholes should be drilled into the first confining layer beneath the uppermost aquifer. The portion of the borehole extending into the confining layer should be plugged properly after a sample is taken.

- Additional boreholes should be installed in numbers and locations sufficient to characterize the geology beneath the site. The number and locations of additional boreholes should be based on data from initial borings and indirect investigation.

- Collection of samples of every significant stratigraphic contact and formation, especially the confining layer should be taken. Continuous cores should be taken initially to ascertain the presence and distribution of small and large scale permeable layers. Once stratigraphic control is established, samples taken at regular, e.g., five foot intervals could be substituted for continuous cores.

TABLE 10-6. APPLICATIONS OF GEOPHYSICAL METHODS TO HAZARDOUS WASTE SITES

APPLICATION	RADAR	ELECTROMAGNETICS	RESISTIVITY	SEISMIC	METAL DETECTOR	MAGNETOMETER
Mapping of Geohydrologic features	1	1	1	1	-	-
Mapping of Conductive Leachates and Contaminant Plumes (ex. Landfills, Acids, Bases)	2	1	1	-	-	-
Locations and Boundary Definition of Buried Trenches with Metal	1	1	2	2	2	2
Location and Boundary Definition of Buried Trenches without Metal	1	1	2	2	-	-
Location and Definition of Buried Metallic Objects (ex. Drums, Ordinance)	2	2	-	-	1	1

1. Primary method - Indicates the most effective method
2. Secondary method - Indicates an alternate approach

Source: EPA, 1982, Geophysical Techniques for Sensing Buried Waste and Waste Migration

TABLE 10-7. FACTORS INFLUENCING DENSITY OF INITIAL BOREHOLES

Factors That May Substantiate Reduced Density of Boreholes:	Factors That May Substantiate Increased Density of Boreholes:
● Simple geology (i.e., horizontal, thick, homogeneous geologic strata that are continuous across site that are unfractured and are substantiated by regional geologic information).	● Fracture zones encountered during drilling.
● Use of geophysical data to correlate well log data.	● Suspected pinchout zones (e.g., discontinuous areas across the site).
	● Geologic formations that are tilted or folded.
	● Suspected zones of high permeability that would not be defined by drilling at 300-foot intervals.
	● Laterally transitional geologic units with irregular permeability (e.g., sedimentary facies changes).

- Boreholes in which permanent wells are not constructed should be sealed with materials at least an order of magnitude less permeable than the surrounding soil/sediment/rock in order to reduce the number of potential contaminant pathways.

- Samples should be logged in the field by a qualified professional in geology.

- Sufficient laboratory analysis should be performed to provide information concerning petrologic variation, sorting (for unconsolidated sedimentary units), cementation (for consolidated sedimentary units), moisture content, and hydraulic conductivity of each significant geologic unit or soil zone above the confining layer/unit.

- Sufficient laboratory analysis should be performed to describe the mineralogy (X-ray diffraction), degree of compaction, moisture content, and other pertinent characteristics of any clays or other fine- grained sediments held to be the confining unit/layer. Coupled with the examination of clay mineralogy and structural characteristics should be a preliminary analysis of the reactivity of the confining layer in the presence of the wastes present.

ASTM or equivalent methods should be used for soil classification, specifically:

- ASTM Method D422-63 for the particle size analysis of soils, which describes the quantitative determination of the distribution of particle sizes in soils; and

- ASTM Methods D2488-69, for the identification and description of soils based on visual examination and simple manual tests.

An adequate number of geologic cross-sections should be presented by the owner or operator. These cross-sections should adequately depict major geologic or structural trends and reflect geologic/structural features in relation to ground-water flow. Additionally, an owner or operator should provide a surface topographic map and aerial photograph of the site. Details regarding the specific requirements for the presentation of geologic data are presented in Section 5 and in Section 1.2.3 of the TEGD (U.S. EPA, 1986).

10.6.2.2 Monitoring Well Installation

The owner or operator is advised to consult Chapter Three of the TEGD (U.S. EPA, 1986) for guidance on monitoring well installation. This chapter provides information on the following topics:

- Drilling Methods for Installing Wells--Section 3.1 (TEGD) discusses a variety of well drilling methods and corresponding applicability to the installation of RCRA monitoring wells. The selection of the actual drilling method that an owner or operator should use at a particular site is a function of site-specific geologic conditions. Of utmost importance is that the drilling method the owner or operator uses will minimize the disturbance of subsurface materials and will not cause contamination of the ground water.

- Monitoring Well Construction Materials--Section 3.2 (TEGD) discusses the selection of construction materials for RCRA monitoring wells which are durable enough to resist chemical and physical degradation, and do not interfere with the quality of ground-water samples. Specific well components that are of concern include well casings, well screens, filter packs, and annular seals.

- Design of Well Intakes--Section 3.3 (TEGD) discusses the design and construction of the intake of monitoring wells so as to: (1) allow sufficient ground-water flow to the well for sampling; (2) minimize the passage of formation materials (turbidity) into the well; and (3) ensure sufficient structural integrity to prevent the collapse of the intake structure.

- Development of Wells--Section 3.4 (TEGD) discusses the requirements for proper development of the monitoring wells to ensure turbid-free ground water samples.

- Documentation of Well Construction Activity--Section 3.5 (TEGD) lists the information required for the design and construction of wells as follows:

    - date/time of construction;
    - drilling method and drilling fluid used;
    - well location (± 0.5 ft);
    - borehole diameter and well casing diameter;
    - well depth (± 0.1 ft);
    - drilling and lithologic logs;
    - casing materials;
    - screen materials and design;
    - casing and screen joint type;
    - screen slot size/length;
    - filter pack material/size;
    - filter pack volume calculations;
    - filter pack placement method;
    - sealant materials (percent bentonite);
    - sealant volume (lbs/gallon of cement);
    - sealant placement method;
    - surface seal design/construction;
    - well development procedure;
    - type of protective well cap;
    - ground surface elevation (± 0.01 ft);
    - top of casing elevation (± 0.01 ft); and
    - detailed drawing of well (including dimensions).

- Specialized Well Design--Section 3.6 (TEGD) discusses two cases which require special monitoring well design: (1) where dedicated pumps are used to draw ground-water samples; and (2) where light and/or dense phase immiscible layers are present.

- Evaluation of Existing Wells--Section 3.7 (TEGD) discusses how to evaluate the ability of existing wells to produce representative ground-water samples.

Particular attention should be paid to the discussion in Section 3.2.1 regarding well casing materials (TEGD). It is imperative that well materials are nonreactive to contaminants that may be present in the ground water. In cases where the facility has existing monitoring wells which could potentially be used in the RFI, the owner or operator should evaluate whether these wells are capable of producing representative ground water samples. A demonstration involving the installation of new well(s) near existing wells and the analysis and comparison of samples for the same parameters from both wells may be necessary if the existing wells' integrity is in question.

10.6.3 Aquifer Characterization

10.6.3.1 Hydraulic Conductivity Tests

In addition to defining the direction of ground-water flow in the vertical and horizontal direction, the owner or operator should identify areas of high and low hydraulic conductivity within each formation. Variations in the hydraulic conductivity of subsurface materials can create irregularities in ground-water flow paths. Areas of high hydraulic conductivity represent areas of greater ground-water flow and, if contaminants are present, zones of potential migration. Therefore, information on hydraulic conductivities is generally required before the owner or operator can make reasoned decisions regarding well placements. It may be beneficial to use analogy or laboratory methods to corroborate results of field tests; however, only field methods provide direct information that is adequate to define the hydraulic conductivity.

Hydraulic conductivity can be determined in the field using single well tests, more commonly referred to as slug tests, which are performed by suddenly adding or removing a slug (known volume) of water from a well or piezometer and observing the recovery of the water surface to its original level. Similar results can be achieved by pressurizing the well casing, depressing the water level, and suddenly releasing the pressure to simulate removal of water from the well. Where slug tests are not appropriate (e.g., in fractured flow aquifers), hydraulic conductivity can be determined by multiple well (pumping) tests.

Slug testing is applied by hydrogeologists in almost all field situations. Interpretation of the results requires some professional judgement, slug test accuracy is reduced when dealing with extreme values of hydraulic conductivity. Very low values (less than 10^{-6} cm/sec) are more accurately measured by a resurg head test after bailing or pumping the well dry. High values (greater than 10^{-2} cm/sec) generally require fast response electronic measurement equipment. High value cases in fractured rock or karst terrain may be misleading in that the slug test is measuring the most permeable fractures or solution channels and may give an artificially high value for the formation as a whole.

When reviewing information obtained from slug tests, several criteria should be considered. First, slug tests are run on one well and, as such, the information obtained from single well tests is limited in scope to the geologic area directly adjacent to the well. Second, the vertical extent of screening will control the part of the geologic formation that is being tested during the slug test. That part of the column above or below the screened interval that has not been tested during the slug test will not have been adequately tested for hydraulic conductivity. Third, the methods used to collect the information obtained from slug tests should be adequate to measure accurately parameters such as changing static water (prior to initiation, during, and following completion of slug test), the amount of water added to, or removed from the well, and the elapsed time of recovery. This is especially important in highly permeable formations where pressure transducers and high speed recording equipment should be used. Lastly, interpretation of the slug test data should be consistent with the existing geologic information (boring log data). It is, therefore, important that the program of slug testing ensure that enough tests are run to provide representative measures of hydraulic conductivity, and to document lateral and vertical variation of hydraulic conductivity in the hydrogeologic subsurface below the site.

It is important that hydraulic conductivity measurements define hydraulic conductivity both in a vertical and horizontal manner across a site. In assessing hydraulic conductivity measurements, results from the boring program used to characterize the site geology should be considered. Zones of high permeability or fractures identified from drilling logs should be considered in the determination of hydraulic conductivity. Additionally, information from coring logs can be used to refine the data generated by slug tests (TEGD, Section 1.3.3).

Techniques for determining hydraulic conductivity are specified in Method 9100, Saturated Hydraulic Conductivity, Saturated Leachate Conductivity, and Intrinsic Permeability; from SW-846, Test Methods for Evaluating Solid Waste, 3rd edition, September, 1986. Method 9100 includes techniques for:

- Laboratory
    - sample collection;
    - constant head methods; and
    - falling head methods.
- Field
    - well construction;
    - well development;
    - single well tests (slug tests); and
    - references for multiple well (pumping) tests.

Cedergren, 1977 also provides an excellent discussion on aquifer tests, including laboratory methods (constant head and falling head), multiple well (pumping) tests (steady-state and nonsteady-state), and single well tests (open-end, packer, and others).

10.6.3.2 Water Level Measurements

Water level measurements are necessary for determining depth to the water table and mapping ground-water contours to determine hydraulic gradients and flow rates. Depths to water are normally measured with respect to the top of casing as in well depth determinations. Several methods are available including the electric sounder and the chalked steel tape.

The electric sounder, although not the most accurate method, is recommended for initial site work because of the minimal potential for equipment contamination and simplicity of use. Sounders usually consist of a conductivity cell at the end of a graduated wire, and a battery powered buzzer. When the cell contacts the water the increased conductivity completes the circuit and allows current to flow to the alarm buzzer. The depth to water can then be read from the graduations on the wire or the wire can be measured directly. This device may not be suitable for use if a potentially flammable or explosive layer (e.g., due to methane gas) is present in the well, unless it is an intrinsically safe device.

The chalked steel tape is a more accurate device for measuring static water levels. The lower 0.5 to 1.0 meters of a steel measuring tape is coated on either side with either carpenter's chalk or any of the various indicating pastes. A weight is attached to the lower end to keep the tape taut and it is lowered into the center of the well (condensate on the casing wall may prematurely wet the tape). A hollow "plopping" sound occurs when the weight reaches water, then the tape is lowered very slowly for at least another 15 cm, preferably to an even increment on the measuring tape. Next, the tape is carefully withdrawn from the well; water depth is determined by subtracting the wetted length of tape from the total length of tape in the well. In small diameter wells, the volume of the weight may cause the water to rise by displacement. In general, the use of indicating paste or chalk should be discouraged although they may not present a significant problem if water samples are not collected. As with all depth measurement devices, the wetted section of the tape and the weight must be thoroughly cleaned before reuse to avoid cross contamination.

The following sections of the TEGD (U.S. EPA, 1986) should be consulted for water level measurement requirements, and information on data interpretation:

- Ground-water level measurement (1.3.1.1);
- Interpretation of ground water level measurements (1.3.1.2);
- Establishing vertical components of ground water flow (1.3.1.3); and
- Interpretation of flow direction (1.3.1.4).

10.6.3.3 Dye Tracing

Dye tracing is a field method used to measure the velocity of ground water for highly permeable strata (such as karst terrain and highly fractured rock media). When the velocity of flowing water and the hydraulic gradient at a common point are known, the permeability can be estimated. The hydraulic gradient (i) of an existing water table can be estimated from wells in the area. If not, observation wells must be installed (Cedergren, 1977).

The procedure used in dye tracing involves the insertion of a dye such as fluorescein sodium into a test hole and observation of the time it takes to emerge in a nearby test pit or on a bank from which seepage is emerging. The average linear velocity, v, is determined by dividing the distance traveled, L, by the time of travel, t. The effective porosity, n_e, is determined from test data for the in-place soil; if no tests are available, it is determined using the values in Table 10-4. The hydraulic conductivity is calculated from the equation:

$$K = \frac{\bar{v}\, n_e}{i}$$

It should be noted that the time required for tracers to move even short distances can be very long unless the formations contain highly permeable strata (Cedergren, 1977). As a result of the limitations of tracer techniques, this type of study is applied only in highly specialized locations. Uncertainties associated with the flow path make interpretation of the results difficult. This technique has been used effectively in conjunction with modeling in complex terrain with the tracer study serving to calibrate the model.

10.6.4 Ground Water Sample Collection Techniques

The procedure for collecting a ground water sample involves the following steps presented in Chapter 4 of TEGD (U.S. EPA, 1986):

- Measurement of static water level elevation (4.2.1);

- Monitoring of immiscible layers (4.2.2);
- Well evacuation (4.2.3);
- Sample withdrawal (4.2.4);
- In situ or field analyses (4.2.5);
- Sample preservation and handling (4.3); and
- Chain-of-custody procedures (4.4).

Collection of static water level elevations on a continuing basis is important to determine if horizontal and vertical flow gradients have changed since initial site characterization, which could necessitate modification of the ground-water monitoring system. Steps should be taken to monitor for the presence and/or extent of light and/or dense phase immiscible organic layers before the well is evacuated for conventional sampling if wastes of this type are present at the facility.

The water standing in the well prior to sampling may not be representative of in situ ground-water quality. Therefore, the owner or operator should remove the standing water in the well so that water which is representative of the formation can replace the standing water. Purged water should be collected and screened with photoionization or organic vapor analyzers, pH, temperature, and conductivity meters. If these parameters and facility background data suggest that the water is hazardous, it should be drummed and disposed of properly.

The technique used to withdraw a ground-water sample from a well should be selected based on a consideration of the parameters which will be analyzed in the sample. To ensure the ground-water sample is representative of the formation, it is important to avoid physically altering or chemically contaminating the sample during the withdrawal process. In order to minimize the possibility of sample contamination, the owner or operator should:

(1) Use only polytetrafluoroethylene (PTFE) or stainless steel sampling devices; and

(2) Use dedicated samplers for each well. (If a dedicated sampler is not available for each well, the sampler should be thoroughly cleaned between sampling events, and blanks should be taken and analyzed to ensure that cross contamination has not occurred.)

Section 4.2.4 of TEGD (U.S. EPA, 1986) includes specific factors to take into consideration regarding sample withdrawal.

Some parameters are physically or chemically unstable and must be tested either in the borehole using a probe (in situ) or immediately after collection using a field test kit. Examples of several unstable parameters include pH, redox potential, chlorine, dissolved oxygen, and temperature. Although specific conductivity (analogous to electrical resistance) is relatively stable, it is recommended that this characteristic also be determined in the field. Most conductivity instruments require temperature compensation; therefore, temperatures of the samples should be measured at the time conductivity is determined.

Many of the constituents and parameters that are included in ground-water monitoring programs are not stable and, therefore, sample preservation may be required. Refer to methods from EPA's Test Methods for Evaluating Solid Waste - Physical Chemical Methods, 1986 (EPA/SW-846 GPO No. 955-001-00000-1) for sample preservation procedures and sample container requirements.

Improper sample handling may lead to sample contamination. Samples should be transferred into their containers in such a way as to minimize any contamination. Handling methods are analyte dependent. Special handling considerations for various analyte types are discussed in Section 4.3.3 of the TEGD (U.S. EPA, 1986).

An adequate chain-of-custody program will allow for the tracing of possession and handling of individual samples from the time of field collection through laboratory analysis. An owner or operator's chain-of-custody program requirements are detailed in Section 4 (Quality Assurance and Quality Control).

Chapter Four of the TEGD (U.S. EPA, 1986) may also consulted for sample collection techniques as well as for analytical procedures, field and laboratory QA/QC requirements, and suggestions for reporting of ground water data. Section 4 of this guidance presents a general discussion of QA/QC. In addition, the owner or operator may also find the following publication useful for sampling information:

- U.S. EPA. September, 1987. Practical Guide for Ground Water Sampling. EPA/600/2-85/104. NTIS PB86-137304. Washington, D.C. 20460.

10.7 Checklist

RFI Checklist - Ground Water

Site Name/Location ______________________________

Type of Unit ______________________________

1. Does waste characterization include the following information? (Y/N)
   - Constituents of concern/supporting indicator parameters ____
   - Concentrations of constituents ____
   - Physical form of waste ____
   - Chemical properties of waste (organic, inorganic, acid, base) and constituents ____
   - pH ____
   - pka ____
   - Viscosity ____
   - Water solubility ____
   - Density ____
   - k_{ow} ____
   - Henry's Law Constant ____
   - Physical and chemical degradation (e.g., hydrolysis) ____

2. Does unit characterizatio include the following information? (Y/N)
   - Age of unit ____
   - Construction integrity ____
   - Presence of liner (natural or synthetic) ____
   - Location relative to ground-water table or bedrock or other confining barriers ____
   - Unit operation data ____
   - Presence of cover or other surface covering ____
   - Presence of on/offsite buildings ____
   - Depth and dimensions of unit ____
   - Inspection records ____
   - Operation logs ____

- Past fire, explosion, or other complaint reports _____
- Existing ground-water monitoring data _____
- Presence of natural or engineered barriers near unit _____

3. Does environmental setting information include the following information?

(Y/N)

Site Soil Characteristics

- Grain size distribution and gradation _____
- Hydraulic Conductivity _____
- Porosity _____
- Discontinuities in soil strata (e.g., faults) _____
- Degree and orientation of subsurface stratification and bedding _____

Ground Water Flow System Characterization (Y/N)

- Use of aquifer _____
- Regional flow cells and flow nets _____
- Depth to water table _____
- Direction of flow _____
- Rate of flow _____
- Hydraulic conductivity _____
- Storativity/specific yield (effective porosity) _____
- Aquifer type (confined or unconfined) _____
- Aquifer characteristics (e.g., homogeneous, isotropic, leaky) _____
- Hydraulic gradient _____
- Identification of recharge and discharge areas _____
- Identification of aquifer boundaries (i.e., areal extent) _____
- Aquitard characteristics (depth, permeability degree of jointing, continuity) _____

RFI Checklist - Ground Water (Continued)

Ground Water Quality Characteristics (Y/N)

- Presence of minerals and organics ______
- Background water quality ______
- Monitoring constituents and indicator parameters ______

4. Have the following data on the initial phase of the release characterization been collected? (Y/N)

   - Extent ______
   - Location ______
   - Shape ______
   - Hydraulic gradient across plume ______
   - Depth to plume ______
   - Chemistry and concentration ______
   - Velocity ______
   - Potential receptors ______

5. Have the following data on the subsequent phase(s) of the release characterization been collected? (Y/N)

   - Extent ______
   - Location ______
   - Shape ______
   - Hydraulic gradient across plume ______
   - Depth to plume ______
   - Chemistry and concentration ______
   - Velocity ______
   - Potential receptors ______

10.8 References

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SECTION 11

SUBSURFACE GAS

11.1 Overview

This section applies to units with subsurface gas releases, primarily landfills, leaking underground tanks, and units containing putrescible organic matter, but may include other units.

The objective of an investigation of a subsurface gas release is to verify, if necessary, that subsurface gas migration has occurred and to characterize the nature, extent, and rate of migration of the release of gaseous material or constituents through the soil. Methane gas should be monitored because it poses a hazard due to its explosive properties when it reaches high concentrations, and also because it can serve as an indicator (i.e., carrier gas) for the migration of hazardous constituents. Other gases (e.g., carbon dioxide and sulfur dioxide) may also serve as indicators. This section provides:

- A recommended strategy for characterizing subsurface gas releases, which includes characterization of the source and the environmental setting of the release, and conducting monitoring to characterize the release itself;

- Recommendations for data organization and presentation;

- Appropriate field methods which may be used in the investigation; and

- A checklist of information that may be needed for release characterization.

The exact type and amount of information required for sufficient release characterization will be site-specific and should be determined through interactions between the regulatory agency and the facility owner or operator during the RFI process. This guidance does not define the specific data required in all instances; however, it identifies possible information which may be necessary to perform release characterizations and methods for obtaining this information. The RFI Checklist, presented at the end of this section, provides a tool for planning and tracking information for subsurface gas release characterizations. This list is not meant to serve as a list of requirements for all subsurface gas releases to soil. Some releases will involve the collection of only a subset of the items listed.

As indicated in the following sections, subsurface gas migrates along the path of least resistance, and can accumulate in structures (primarily basements) on or off the facility property. If this occurs, it is possible that an immediate hazard may exist (especially if the structures are used or inhabited by people) and that interim corrective measures may be appropriate. Where conditions warrant, the owner or operator should immediately contact the regulatory agency and consider immediate measures (e.g., evacuation of a structure).

Case Study No. 8 in Volume IV (Case Study Examples) provides an example of a subsurface gas investigation.

11.2 Approach for Characterizing Subsurface Gas Releases

11.2.1 General Approach

Characterization of subsurface gas releases can be accomplished through a phased monitoring approach. A recommended strategy for characterizing subsurface gas releases is shown in Table 11-1. The outlined strategy will provide an acceptable technical approach to effectively characterize the nature and extent of subsurface gas releases from units.

The collection and review of information for characterization of the contaminant source and the environmental setting will be the primary basis for development of a conceptual model of the release and subsequent development of monitoring procedures used to characterize the release. This input data should initially be compiled from available sources. Additional data collection to characterize the contaminant source and environmental setting may be necessary.

Table 11-1

Recommended Strategy for Characterizing Releases of Subsurface Gas[1]

INITIAL PHASE

1. Collect and review preliminary information for use in formulating monitoring procedures:

   - Characterization of the contaminant source
     - Waste characterization
     - Unit characterization
   - Characterization of the environmental setting
     - Natural and engineered barriers
     - Climate and meteorological conditions
     - Receptors

2. Identify and collect additional information necessary to characterize release

   - Spatial extent of release
   - Release constituents present and concentration levels
   - Inter-media transport
   - Develop conceptual model of release

3. Develop monitoring procedures:

   - Determine monitoring constituent(s)
   - Select indicator parameter(s)
   - Sampling approach selection
   - Sampling schedule
   - Monitoring locations
   - Analytical plans
   - QA/QC procedures

4. Conduct Initial Monitoring Phase:

   - Use subsurface gas migration model to estimate release dimensions (plot 1.0 and 0.25 lower explosion limit isopleths for methane).
   - Monitor ambient air and shallow boreholes around the site using portable survey instruments to detect methane and other indicator parameters.
   - Use results of above two steps to refine conceptual model and determine sampling locations and depths; conduct limited well installation program. Monitor well gas and shallow soil boreholes for indicators and constituents.
   - Monitor surrounding structures (e.g., buildings and engineered conduits) for other indicator constituents.

5. Collect, evaluate and report results:

   - Compare methane results with lower explosion limit (LEL) and 0.25 LEL and report results immediately to regulatory agency if these values are exceeded.
   - Determine completeness and adequacy of collected data

Table 11-1 (Continued)

Recommended Strategy for Characterizing Releases of Subsurface Gas[1]

- Summarize and present data in appropriate format
- Determine if monitoring program objectives were met
- Determine if data are adequate to describe nature, rate and extent of release
- Report results to regulatory agency

SUBSEQUENT PHASES (If Necessary)

1. Identify additional information necessary to characterize release:
    - Modify conceptual model and identify additional information needs
    - Selection of monitoring constituents for subsequent phase
    - Spatial extent of subsurface gas migration
    - Concentration levels of methane and other indicators and additional monitoring constituents
    - Evaluate potential role of inter-media transport
2. Expand initial monitoring as necessary:
    - Expand subsurface gas well monitoring network
    - Add or delete constituents and parameters
    - Expand number of structures subject to monitoring
    - Increase or decrease monitoring frequency
3. Conduct subsequent monitoring phases:
    - Perform expanded monitoring of area for methane and other indicator and specific monitoring constituents.
    - Further monitoring of surrounding structures if warranted.
4. Collect, evaluate and report results/identify additional information necessary to characterize release:
    - Compare monitoring results to health and environmental criteria and identify/respond to emergency situations and identify priority situations that warrant interim corrective measures - notify regulatory agency immediately
    - Determine completeness and adequacy of collected data
    - Summarize and present data in appropriate format
    - Determine if monitoring program objectives were met
    - Determine if data are adequate to describe nature, rate, and extent of release
    - Identify additional information needs
    - Determine need to expand monitoring system
    - Evaluate potential role of inter-media transport
    - Report results to regulatory agency

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[1] The possibility for inter-media transport of contamination exists, and should be anticipated throughout the investigation.

The subsurface pathway data collection effort should be coordinated, as appropriate, with similar efforts for other media investigations.

Development of monitoring procedures should include determining the specific set of subsurface gas indicators and constituents for monitoring. Methane and carbon dioxide can be used to identify the presence of subsurface gas during initial screening monitoring. Subsequent monitoring will generally involve these gases, but may also involve various constituents. Development of the monitoring procedures should also include selection of the appropriate field and analytical methods. Selection of these methods will be dependent on site and unit specific conditions.

An initial monitoring phase should be implemented using screening techniques and appropriate monitoring constituent(s). A subsurface gas migration model can be used, as applicable, as an aid in selection of monitoring locations. Subsequent monitoring will generally be necessary if subsurface gas migration is detected during the initial survey. This additional monitoring may include a wider range of constituents.

Characterization of a subsurface gas release can involve a number of tasks to be completed throughout the course of the investigation. These tasks are listed in Table 11-2 with associated techniques and data outputs.

As monitoring data become available, both within and at the conclusion of discrete investigation phases, it should be reported to the regulatory agency as directed. The regulatory agency will compare the monitoring data to applicable health and environmental criteria to determine the need for (1) interim corrective measures; and (2) a Corrective Measures Study. In addition, the regulatory agency will evaluate the monitoring data with respect to adequacy and completeness to determine the need for any additional monitoring efforts. The health and environmental criteria and a general discussion of how the regulatory agency will apply them are supplied in Section 8. A flow diagram illustrating RFI decision points is provided in Section 3 (See Figure 3-2).

TABLE 11-2
RELEASE CHARACTERIZATION TASKS FOR SUBSURFACE GAS

Investigatory Tasks	Investigatory Techniques	Data Presentation Formats/Outputs
1. Waste/Unit Characterization		
- Identification of waste constituents of concern	- See Sections 3, 7 and Appendix B	- Listing of potential monitoring constituents
- Identification of unit characteristics which promote a subsurface gas release	- See Section 7	- Description of the unit, if active, and operational conditions concurrent with subsurface gas sampling
2. Environmental Setting Characterization		
- Definiation of climate	- Climate summaries for regional National Weather Service stations	- Tabular summaries for parameters of interest
- Definition of site-specific meteorological conditions	- Meteorological data from regional National Weather Service stations	- Tabular listing for parameters of interest concurrent with subsurface gas sampling
- Definition of soil conditions	- See Section 9 (e.g., porosity, moisture content, organic carbon content, etc.)	- Soil physical properties
- Definition of site-specific terrain	- See Sections 7, 9 and Appendix A	- Topographic map of site area
- Identification of subsurface gas migration pathways	- Review of unit design and environmental setting	- Identification of possible migration pathways
	- Review of water level table	- Depth to water table
- Identification and location of engineered conduits	- Examination of maps, engineering diagrams, etc.	- Description of the examination
	- Ground penetrating radar (See Appendix C.)	- Results of study
- Identification and location of surrounding structures	- Survey of surrounding area	- Map with structures identified
3. Release Characteriziation		
- Model extent of release	- Gas migration model (See Appendix D)	- Estimated methane concentration isopleths for LEL and 0.25 LEL
- Screening evaluation of subsurface gas release	- Shallow borehole monitoring and monitoring in surrounding buildings for indicators and specific constituent(s)	- Listing of concentrations levels
- Measurement for specific constituents	- Selected gas well installation and monitoring	- Tables of concentrations
		- Detailed assessment of extent and magnitude of releases
	- Monitoring in surround buildings	- Tables of concentrations

Not withstanding the above process, the owner or operator has a continuing responsibility to identify and respond to emergency situations and to define priority situations that may warrant interim corrective measures. For these situations, the owner or operator is directed to obtain and follow the RCRA Contingency Plan requirements under 40 CFR Part 264, Subpart D.

11.2.2 Inter-media Transport

Contaminated ground water and contaminated soil can result in releases of gaseous constituents via subsurface migration, primarily due to volatilization of organic constituents. Information collected from ground-water and soil investigations may provide useful input data for the subsurface gas pathway characterization. It may also be more efficient to jointly conduct monitoring programs for such related media (e.g., concurrent ground water and subsurface gas migration monitoring programs).

Subsurface gas migration also has the potential for inter-media transport (e.g., transfer of contamination from subsurface gas to the soil and air media). Therefore, information from the subsurface gas migration investigation will also provide useful input for assessing soil contamination and potential air emissions.

11.3 Characterization of the Contaminant Source and the Environmental Setting

The type of waste managed in the unit will determine the conditions under which the gas can be generated, and the type of unit and characteristics of the surrounding environment (e.g., soil type and organic content) establishes potential migration pathways. Units which may be of particular concern for subsurface gas releases contain putrescible organic material and generally include below grade landfills, units closed as landfills (e.g., surface impoundments), and underground tanks. These types of units may have waste deposited or stored at such depths as to allow for subsurface gas generation by volatilization or decomposition of organic wastes and subsequent migration (see Figures 11-1 and 11-2).

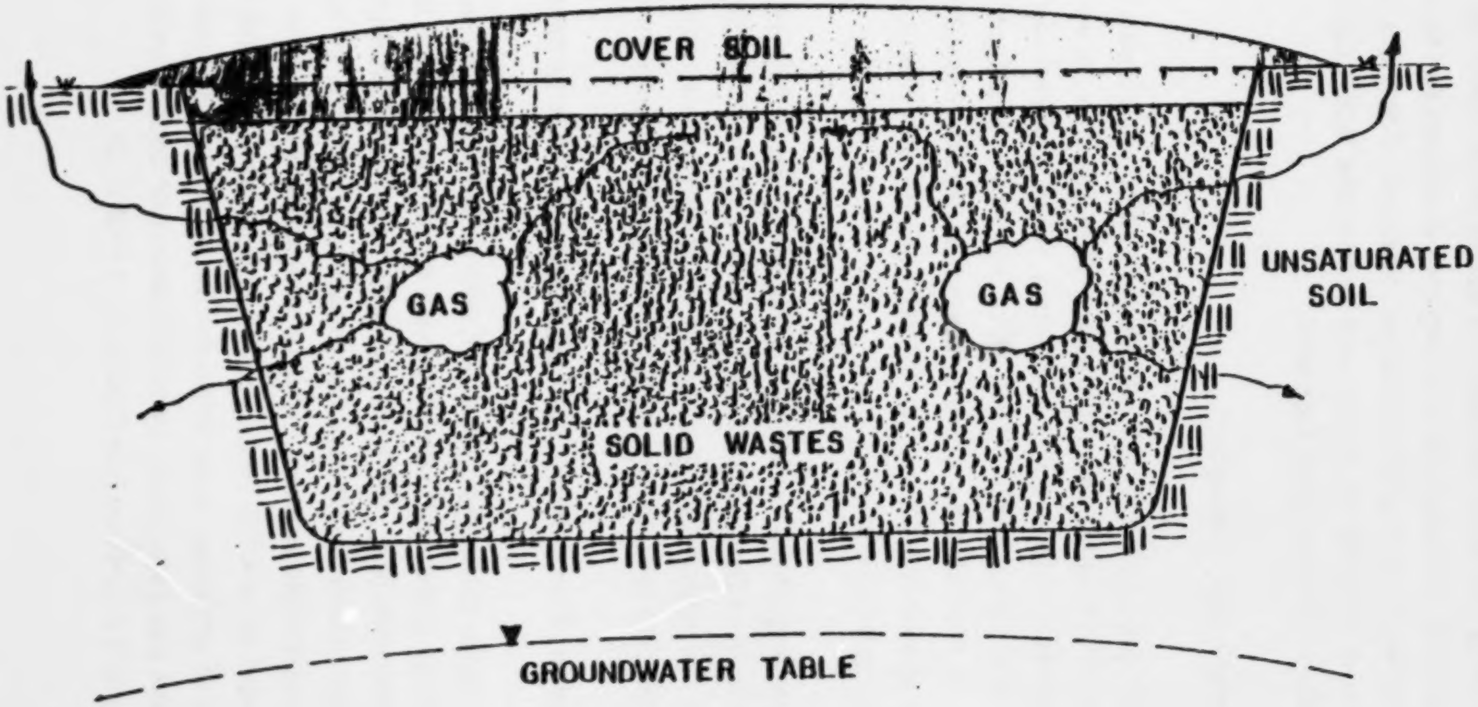
COVER SOIL
GAS
GAS
UNSATURATED SOIL
SOLID WASTES
GROUNDWATER TABLE

Figure 11-1. Subsurface Gas Generation/Migration in a Landfill
(Note: Gas may also migrate slowly through cover soil.)

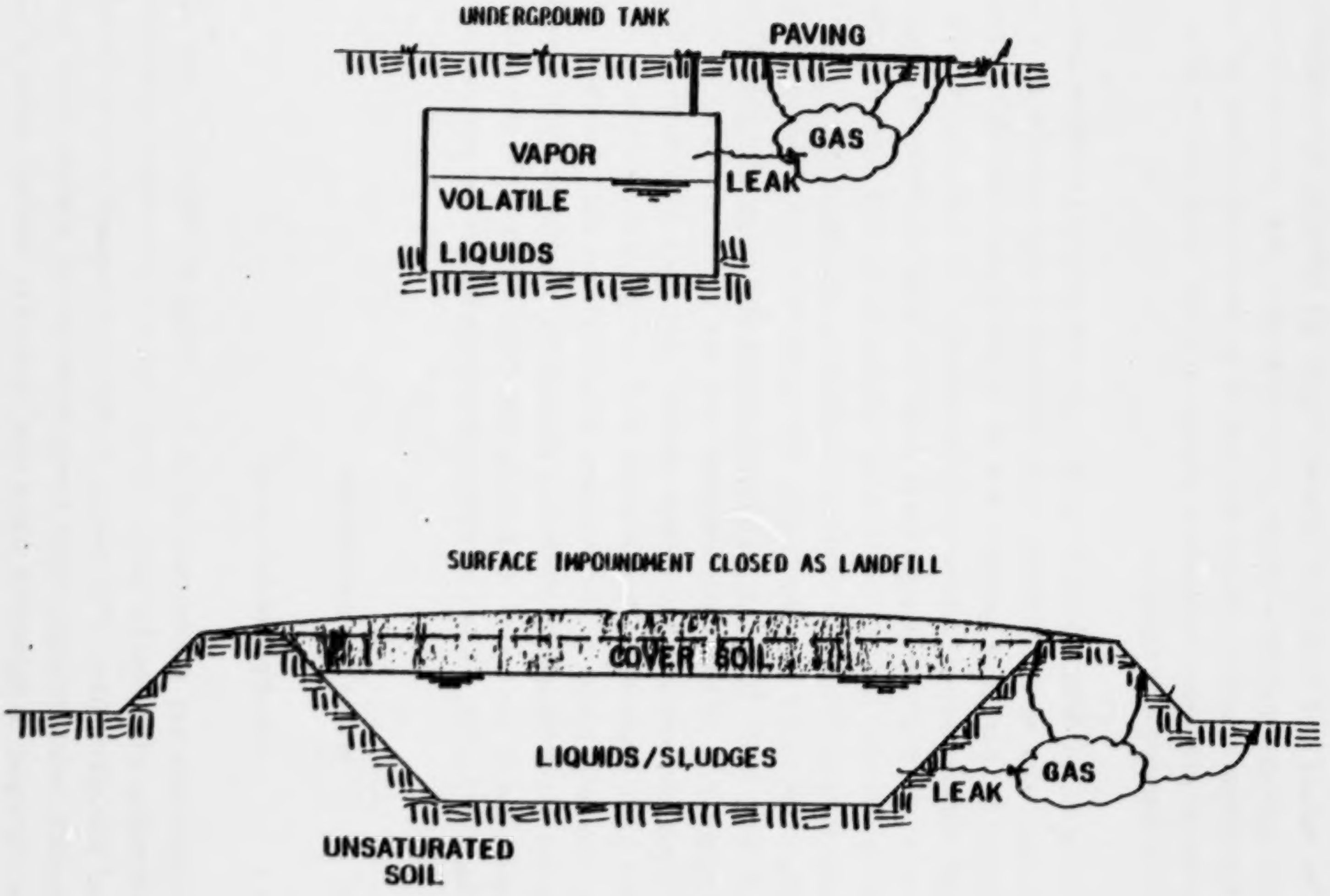
UNDERGROUND TANK
PAVING
GAS
VAPOR
LEAK
VOLATILE
LIQUIDS
SURFACE IMPOUNDMENT CLOSED AS LANDFILL
COVER SOIL
LIQUIDS/SLUDGES
GAS
LEAK
UNSATURATED SOIL

Figure 11-2. Subsurface Gas Generation/Migration from Tanks and Units Closed as Landfills (Note: Gas may also migrate slowly through cover soil.)

The nature and extent of contamination are affected by environmental processes such as dispersion, diffusion, and degradation, that can occur before and after the release occurred. Factors that should be considered include soil physical and chemical properties, subsurface geology and hydrology, and in some cases, climatic or meteorologic patterns.

The principle components of "landfill gas" are generally methane and carbon dioxide produced by the anaerobic decomposition of organic materials in wastes. Methane is of particular concern due to its explosive/flammable properties, although other gases of concern could be present. The presence of these other gases in a unit is primarily dependent upon the types of wastes managed, the volatilities of the waste constituents, temperature, and possible chemical interactions within the waste. Previous studies (e.g., Hazardous Pollutants in Class II Landfills, 1986, South Coast Air Quality Management District, El Monte, California and U.S. EPA. 1985. Technical Guidance for Corrective Measures - Subsurface Gas. Washington, D.C. 20460) have indicated that the predominant components of landfill gas are methane and carbon dioxide. Methane is generally of greater concentration, however, carbon dioxide levels are generally also high, especially during the early stages of the methane generation process. Concentrations of subsurface gas constituents which may accompany methane/carbon dioxide are generally several orders of magnitude less than methane. In some cases (e.g., associated with acidic refinery wastes) sulfur dioxide may be the primary subsurface gas.

11.3.1 Waste Characterization

11.3.1.1 Decomposition Processes

Subsurface gas generation occurs by biological, chemical, and physical decomposition of disposed or stored wastes. Waste characteristics usually affect the rate of decomposition. The owner or operator should review unit-specific information (waste receipts, waste composition surveys, and any other records of wastes managed) to determine waste type, quantities, location, dates of disposal, waste moisture content, organic content, etc.

The three decomposition processes known to occur in the production of subsurface gases are biological decomposition, chemical decomposition, and physical decomposition. These are discussed below:

11.3.1.1.1 Biological Decomposition

The extent of biological decomposition and subsequent gas generation from a given waste is related to the type of unit. Biological decomposition, due primarily to anaerobic microbial degradation, is significant in most landfills and units closed as landfills which contain organic wastes. Generally, the amount of gas generated in a landfill is directly related to the amount of organic matter present.

Organic wastes such as food, sewage sludges, and garden wastes decompose rapidly, resulting in gas generation shortly after burial, with high initial yields. Much slower decomposing organic wastes include paper, cardboard, wood, leather, some textiles and several other organic components. Inorganic and inert materials such as plastics, man-made textiles, glass, ceramics, metals, ash, and rock do not contribute to biological gas production. At units closed as landfills, waste types that undergo biological decomposition might include bulk organic wastes, food processing sludges, treatment plant sludges, and composting waste.

Waste characteristics can increase or decrease the rate of biological decomposition. Factors that enhance anaerobic decomposition include high moisture content, adequate buffer capacity and neutral pH, sufficient nutrients (nitrogen and phosphorus), and moderate temperatures. Characteristics that generally decrease biological decomposition include the presence of acidic or basic pH, sulfur, soluble metals and other microbial toxicants. The owner or operator should review the waste characteristic information to document if biological decomposition and subsequent gas generation may be occurring.

Under anaerobic conditions, organic wastes are primarily converted by microbial action into carbon dioxide and methane. Trace amounts of hydrogen, ammonia, aromatic hydrocarbons, halogenated organics, and hydrogen sulfide may also be present. With regard to subsurface migration, the primary gases of concern are methane (because of its explosive properties) and constituents that may be present in amounts hazardous to human health or the environment.

11.3.1.1.2 Chemical Decomposition

Gas production by chemical reaction can result from the disposal or storage of incompatible wastes. Reactive or ignitable wastes can produce explosive or heat-producing reactions, resulting in rapid production of gases, and increased pressures and temperatures. Under acidic conditions, a strong oxidizing agent can react with organic wastes to produce carbon dioxide and ammonia which can migrate from the unit, possibly providing a transport mechanism for other gaseous components.

Under typical conditions, gas production from chemical reactions is not expected to occur at landfills or units closed as landfills. However, volatile liquids stored in underground tanks may have a significant potential to create a release by chemical reaction. Good waste management practices, particularly the proper design and operation (e.g., pressure-relief valves and leak detection systems) of underground tanks can minimize the potential for gas release.

11.3.1.1.3 Physical Decomposition

Physical decomposition phenomena include volatilization and combustion. Volatilization can result in subsurface gas generation in underground tanks if there is a leak or puncture. The greater a compound's vapor pressure, the greater will be its potential to volatilize. Maintenance of underground tanks (e.g., pressure-relief valves and leak detection systems) can minimize volatilization.

Combustion processes (e.g., underground fires) sometimes occur at active landfills and result in subsurface gas release. Combustion can convert wastes to byproducts such as carbon dioxide, carbon monoxide, and trace toxic components. Combustion processes can also accelerate chemical reaction rates and biological decomposition, creating greater potential for future subsurface gas generation and subsequent release. The owner or operator should review facility records to determine if combustion has occurred and when.

11.3.1.2 Presence of Constituents

Subsurface gas generation and migration of methane is of concern because of its explosive properties. In addition, methane and other decomposition gases can facilitate the migration of volatile organic constituents that may be of concern because of potential toxic effects. Subsurface gas migration due to leaks from subsurface tanks may also be associated with a variety of volatile organic constituents.

In determining the nature of a release, it may be necessary to determine the specific waste constituents in the unit. Two means of obtaining these data are:

(1) Review of facility records. Review of facility records may not provide adequate information (e.g., constituent concentrations) for RFI purposes. For example, facility records of waste handled in the unit may only indicate generic waste information. Knowledge of individual constituents and concentrations is generally needed for purposes of the RFI.

(2) Conducting waste sampling and analysis. When facility records do not indicate the specific constituents of the waste which are likely to be released and may migrate as subsurface gas, direct waste characterization may be necessary. This effort, aimed at providing compound specific data on the waste, can be focused in terms of the constituents for which analysis should be performed through review of the waste types in the unit. In some cases, however, the generic waste description (e.g., flammable liquids) will not give an indication of the specific constituents present, and analysis for all of the constituents of concern as gaseous releases (See Appendix B, List 2) may be required.

Additional guidance on identification of monitoring constituents is presented in Section 3.6. Section 7 provides guidance on waste characterization.

11.3.1.3 Concentration

Determination of concentrations of the constituents of concern in the waste may indicate those constituents which are of prime concern for monitoring. The concentration of a constituent in a waste (in conjunction with its physical/chemical properties and total quantity) provides an indication of the gross quantity of material that may be released in the gaseous form.

11.3.1.4 Other Factors

In addition to the factors described above, determination of the potential for volatilization of the waste constituents will help determine if they may be released. The parameters most important when assessing the potential for volatilization of a constituent include the following:

- Water solubility. The solubility in water indicates the maximum concentration at which a constituent can dissolve in water at a given temperature. This value can be used to estimate the distribution of a constituent between the dissolved aqueous phase in the unit and the undissolved solid or immiscible liquid phase. Considered in combination with the constituent's vapor pressure, it can provide a relative assessment of the potential for volatilization.

- Vapor pressure. Vapor pressure refers to the pressure of vapor in equilibrium with a pure liquid. It is best used in a relative sense; constituents with high vapor pressures are more likely to be released in the gaseous form than those with low vapor pressues, depending on other factors such as relative solubility and concentration (i.e., at high concentrations releases can occur even though a constituent's vapor pressure is relatively low).

- Octanol/water partition coefficient. The octanol/water partition coefficient indicates the tendency of an organic constituent to sorb to organic components of the soil or waste matrices of a unit. Constituents with high octanol/water partition coefficients will adsorb readily to organic carbon, rather than volatilizing to the atmosphere. This is particularly important in landfills and land treatment units, where high organic carbon contents in soils or cover material can significantly reduce the release potential of vapor phase constituents.

- Partial pressure. For constituents in a mixture, particularly in a solid matrix, the partial pressure of a constituent will be more significant than the pure vapor pressure. In general, the greater the partial pressure, the greater the potential for release. Partial pressures will be difficult to obtain. However, when waste characterization data is available, partial pressuers can be estimated using methods commonly found in engineering and environmental science handbooks.

- Henry's Law constant. Henry's law constant is the ratio of the vapor pressure of a constituent and its aqueous solubility (at equilibrium). It can be used to assess the relative ease with which the compound may be removed from the aqueous phase via vaporization. It is accurate only when used in evaluating low concentration wastes in aqueous solution. Thus it will be most useful when the unit being assessed is a surface impoundment or tank containing dilute wastewaters. As the value increases, the potential for significant vaporization increases, and when it is greater than 0.001, rapid volatilization will generally occur.

- Raoult's Law. Raoult's Law can be used to predict releases from concentrated aqueous solutions (i.e., solutions over 10% solute). This will be most useful when the unit contains concentrated waste streams.

11.3.2 Unit Characterization

Unit design (e.g., waste depth, unit configuration, and cover materials) also affects gas generation. Generally, the amount of gas generated increases with landfill volume and often with landfill depth. Deeper landfills have a proportionally larger anaerobic zone, greater insulation and compaction, and are more likely to confine gas production. Deeper landfills, such as trench fills or canyon fills, can trap gases along confining sidewalls and bottom bedrock or ground water. Daily, interim, and final cover soils can confine gases within the landfill. This is particularly true for low permeability cover soils (e.g., clays) which impede vertical gas migration. Conversely, mound or shallow landfills have large surface areas through which gases can vent more easily.

Unit operations, such as methods and procedures used to segregate and isolate inert wastes, to prevent moisture infiltration, to compact and increase the density of the waste, and to minimize or prevent mixing of waste types, can affect resultant releases of subsurface gases. Daily covering of the unit may inhibit decomposition and thus gas generation and subsequent migration.

Certain units have a high potential for allowing the movement of subsurface gas. These units are those that receive and/or store large volumes of decomposable wastes, volatile organic liquids, or highly reactive materials. Subsurface gas migration may occur especially when major portions of a land-based unit are below grade. Gas generated by these units can migrate vertically and laterally from the unit, following the path of least resistance.

Some units are operated above grade or in relatively shallow soils (e.g., surface impoundments, land treatment units). The potential for subsurface gas migration from such units is usually low. Gases generated by such units will generally be vented to the atmosphere unless prevented by a natural barrier (e.g., frozen ground) or an engineered barrier (e.g., soil cover).

Information on unit operations will therefore be important in assessing the potential for subsurface gas migration. Unit operational data may also be required concurrent with any subsurface gas sampling activities. It is particularly important to obtain operational data on any gas collection system in use at the time of sampling. These gas collection systems can significantly affect subsurface gas migration rates, patterns and constituent concentration levels.

Generally, the units that pose the greatest potential for subsurface gas migration include landfills, sites closed as landfills, and underground storage tanks. These are discussed below.

11.3.2.1 Landfills

Gas generated in landfills can vent vertically to the atmosphere and/or migrate horizontally through permeable soil, as shown in Figure 11-1. Closure of the landfill or periodic covering of cells or lifts with impermeable caps may impede the vertical movement of the gases, forcing them to migrate laterally from the unit. Gas migration laterally through the subsurface (e.g., through underground utility line channels or sand lenses) may accumulate in structures on or off the facility property.

11.3.2.2 Units Closed as Landfills

Gas generation and subsequent migration is likely to occur at units closed as landfills containing organic wastes, as previously discussed. Although surface impoundments and waste piles may be closed as landfills, they tend to produce less gas than landfills because they generally contain smaller quantities of decomposable and volatile wastes and are generally at shallow depths. Closure of such units with an impermeable cover will, however, increase the potential for lateral gas movement and accumulation in onsite and offsite structures (see Figure 11-2).

11.3.2.3 Underground Tanks

Subsurface gas release and subsequent migration may occur if an underground tank is leaking. Underground tanks frequently contain volatile liquids that could enter the unsaturated zone should a leak occur (see Figure 11-2).

11.3.3 Characterization of the Environmental Setting

11.3.3.1 Natural and Engineered Barriers

Subsurface conditions at the site should be evaluated to determine likely gas migration routes. Due to the inherent mobility of gases, special attention must be paid to zones of high permeability created by man-made, biological, and physical weathering action. These zones include backfill around pipes, animal burrows, solution channels, sand and/or gravel lenses, desiccation cracks, and jointing in bedrock. The presence of dead rodents, snakes and other burrowing animals is usually a good indication of a potential subsurface gas pathway.

Natural and engineered barriers can also affect gas migration, generally by inhibiting migration pathways. Natural barriers to gas migration include surface water, ground water, and geologic formations. Engineered barriers include walls, onsite structures, underground structures, caps, liners, and other design features. On the other hand, preferred pathways for subsurface gas migration may result from previous underground construction (e.g., underground utility lines) that can facilitate gas flow. Natural and engineered barriers are discussed in more detail below.

11.3.3.1.1 Natural Barriers

Surface water, ground water, and saturated soils can slow down or control the direction of subsurface gas migration. Gases encountering these barriers will follow the pathway of least resistance, usually through unsaturated porous soil.

Geologic barriers can also impede or control the route of subsurface gas migration. For example, soil type is an important factor in gas migration. Gravels and sands allow gas to migrate readily, particularly sand/gravel lenses, while clayey gravels and sandy and organic clays tend to impede gas movement. Underground utility trenches, backfill with granular materials, filled-in mine shafts, and tunnels or natural caverns can also serve to channel subsurface gas flow. Climatic conditions such as precipitation or freezing can reduce the porosity of surface soils, thereby impeding upward gas movement. Information regarding characterization of soils is provided in Section 9 (Soils).

11.3.3.1.2 Engineered Barriers

Landfills and units closed as landfills may use caps and liners to prevent moisture infiltration and leachate percolation to ground water. Caps can contribute to horizontal gas movement when upward migration to the surface is restricted (as shown in Figure 11-1). Liners tend to impede lateral migration into the surrounding unsaturated soils. The owner or operator should evaluate cap/liner systems (type, age, location, etc.) to determine potential gas migration pathways.

Similar to liners, slurry walls used to border landfill units can retard lateral gas movement. With respect to underground tanks, caps and liners are not typically used. Tanks are often placed into soils with sand or gravel backfill during installation, followed by paving on the surface. Thus, any escaping gases from a leaking underground tank may migrate laterally along the path of least resistance adjacent to the units. The owner or operator should evaluate tank construction, and age, integrity, and location.

11.3.3.2 Climate and Meteorological Conditions

The climate of the site should be defined to provide background information for assessing the potential for subsurface gas migration, identifying migration pathways, and designing the subsurface gas migration monitoring system. Climatic information, on an annual and monthly or seasonal basis, should be collected for the following parameters:

- Temperature means/extremes and frost season (which indicates the potential for impeding the upward migration of the subsurface gas, thus confining the gas within the ground);
- Precipitation means and snowfall (which indicates the potential for "trapping" as well as an indication of soil moisture conditions which affect subsurface gas migration); and
- Atmospheric pressure means (which indicates the potential for gaseous releases to ambient air from a unit of concern).

The primary source of climate information for the Unites States is the National Climatic Data Center (Asheville, NC). The National Climatic Data Center can provide climate summaries for the National Weather Service station nearest to the site of interest. Standard references for climatic information also include the following:

Local Climatological Data - Annual Summaries with Comparative Data, published annually by the National Climatic Data Center;

Climates of the States, National Climatic Data Center; and

Weather Atlas of the United States, National Climatic Data Center.

Meteorological data for the above parameters should also be obtained concurrently with subsurface gas sampling activities. As previously discussed, these meteorological conditions can influence subsurface gas migration rates, patterns and concentration levels. Therefore, these data are necessary to properly interpret subsurface gas sampling data. Concurrent meteorological data for the sampling period can be obtained from the National Climatic Data Center for National Weather Service stations representative of the site area. In some cases, onsite meteorological data will also be available from an existing monitoring program or associated with an RFI characterization of the air media (See Section 12).

11.3.3.3 Receptors

Receptor information needed to assess potential subsurface gas exposures includes the identification and location of surrounding buildings and potential sensitive receptors (e.g., residences, nursing homes, hospitals, schools, etc.). This information should also be considered in the developing monitoring procedures. Additional discussion of potential receptors is provided in Section 2.

11.4 Design of a Monitoring Program to Characterize Releases

Existing data should help to indicate which units have the potential to generate methane or other gases or constituents of concern. Such information can be found in construction or design documents, permit and inspection reports, records of waste disposal, unit design and operation records, and documentation of past releases.

Units of concern should be identified on the facility's topographic map. The location and areal extent of these units can be determined from historical records, aerial photographs, or field surveys. The depths and dimensions of underground structures, locations of surrounding buildings, and waste-related information should be identified. Waste management records may provide information on waste types, quantities managed, location of waste units, and dates of waste disposal. Waste receipts, waste composition surveys, and records of waste types (e.g., municipal refuse, bulk liquids, sludges, contaminated soils, industrial process wastes or inert materials) should be reviewed. For underground tanks, liquid waste compositions, quantities, and physical properties should be determined.

Review of unit design and operation records may provide background information on units of concern. These records may include engineering design plans, inspection records, operations logs, damage or nuisance litigation, and routine monitorng data. Also, for landfills and units closed as landfills, data may include the presence and thickness of a liner, ground-water elevations, waste moisture contents, type and amount of daily cover, records of subsurface fires, and in-place leachate and/or gas collection systems. Historical information on underground tank integrity may be contained in construction and monitoring records. Records of past releases may provide information on problems, corrective measures, and controls initiated.

The owner or operator should review records of subsurface conditions to determine potential migration pathways. Aerial photographs or field observations should identify surface water locations. Infrared aerial photography or geological surveys from the USGS can be used as preliminary aids to identify subsurface geologic features and ground-water location. In addition to obtaining and reviewing existing information, a field investigation may be necessary to confirm the location of natural barriers. The local soil conservation service will often have information describing soil characteristics (e.g., soil type, permeability, particle size) or a site specific investigation may need to be conducted. (Soil information sources are discussed in Section 9). Climatic summaries (e.g., temperature, rainfall, snowfall) can be obtained from the National Climatic Data Center for the National Weather Service station nearest to the site of interest (Specific climatic data references are cited in Section 12). Historical records of the site (prior use, construction, etc.) should also be reviewed to identify any factors affecting gas migration routes. The monitoring program should also address any engineered structures affecting the migration pathway.

In addition to the above, the owner or operator should examine the units and surrounding area for signs of settlement, erosion, cracking of covers, stressed or dead vegetation, dead rodents, snakes and other burrowing animals, contamination of surface waters, odors, elevated temperatures in any existing monitoring wells, and for venting of smoke or gases. The condition of any existing gas monitoring systems and containment or collection systems should also be examined, as well as any structural defects in tanks or liners. Any overflow/alarm shut off systems, subsurface leak detection systems, secondary containment structures (e.g., concrete pads, dikes or curbs) or other safety systems for early detection of potential gas releases should be checked.

By reviewing all existing information, the owner or operator should be able to develop a conceptual model of the release and design a monitoring program to characterize the release.

11.4.1 Objectives of the Monitoring Program

Characterization of subsurface gas releases can be accomplished through a phased monitoring approach. The objective of initial monitoring should be to verify suspected releases, if necessary, or to begin characterizing known releases. Monitoring should include methane and other indicators such as carbon dioxide, as well as individual constituents if appropriate. If initial monitoring verifies a suspected release, the owner or operator should expand the monitoring program to determine the vertical and horizontal extent of the release, as well as the concentrations of all constituents of concern in the release.

The full extent of the release can be determined through additional shallow borehole and gas monitoring well locations. The goal of this further characterization will be to identify the boundary of gas migration, including the leading edge of the migration.

A great deal of the effort conducted during any subsequent phase may involve investigating anomalous areas where subsurface conditions are non-uniform. In these situations, the gas migration characteristics may differ from surrounding areas. Consequently, non-random sampling techniques are generally most appropriate to monitor these areas. The location of additional gas wells and shallow boreholes at the sites of subsurface anomalies will provide information regarding the migration pattern around these anomalous areas. Also, because gas well installation may be conducted only to a limited extent under the initial monitoring phase, additional wells may need to be installed.

The monitoring program should also address the selection of constituents of concern, sampling frequency and duration, and the monitoring system design.

11.4.2 Monitoring Constituents and Indicator Parameters

As discussed above, the number and identity of potential subsurface gas constituents will vary on a site-specific basis. Constituents to be included for monitoring depends primarily on the type of wastes received. For example, if an underground storage tank contains specific constituents, they should be considered during subsurface gas monitoring activities. The guidance provided in Section 3 and the lists provided in Appendix B should be used to determine a select set of constituents and indicator parameters for subsurface gas monitoring.

Methane should be used as the primary indicator of subsurface gas migration during the initial and any subsequent monitoring phases. Supplemental indicators (e.g., carbon dioxide and sulfur dioxide) may also be used as appropriate. Field screening equipment should be used to detect the presence of methane in terms of the lower explosive limit (LEL). The LEL for methane is 5 percent by volume, which is equivalent to 50,000 ppm. Individual constituents should also be monitored. In addition, oxygen detectors and nitrogen analyses can be used to confirm the representativeness of all subsurface gas well samples obtained. (The presence of oxygen and nitrogen in well samples indicates the intrusion of ambient air into the well during monitoring. Samples containing ambient air would result in an underestimate of methane and other indicators as well as specific monitoring constituents.)

Methane concentrations observed during the initial monitoring phase which exceed the LEL at the property boundary or 0.25 the LEL at surrounding structures, would warrant initiation of subsequent monitoring phases and possibly, consideration of interim corrective measures. Similarly, the presence of individual constituents would also trigger the need for subsequent monitoring phases.

Regardless of the degree to which monitoring constituents can be limited by site-specific data, analyses for all constituents identified as applicable in Appendix B

(List 2) will generally be necessary for the subsurface gas medium at selected monitoring locations.

11.4.3 Monitoring Schedule

A monitoring schedule should be established and described in the RFI Work Plan. This schedule should describe the sampling frequency, the duration of the sampling effort, and the conditions under which sampling should occur.

During initial monitoring, bar punch probe (See Section 11-6) monitoring for methane and appropriate constituents should be conducted at least twice over the course of one week. Monitoring the wells for methane and constituents should be conducted at least once a week for one month. (Subsurface gas wells should not be monitored for at least 24 hours after installation to allow time for equilibration.) Surrounding buildings should be monitored at least once a week for one month.

During any subsequent monitoring phases, more extensive sampling may be needed to adequately characterize the nature and extent of the release. Monitoring of wells and buildings for methane and constituents should be conducted every other day for a two week period to account for daily fluctuations in gas concentrations.

Conditions for sampling should also be defined. Sampling should generally not be performed if conditions conducive to decreasing gas concentrations are present (e.g., subsurface gas pressure at less than atmospheric pressure). In these cases, sampling should be delayed until such conditions pass. Subsurface gas pressures have a diurnal cycle and are generally at a maximum during the afternoon.

11.4.4 Monitoring Locations

11.4.4.1 Shallow Borehole Monitoring

Areas identified for subsurface gas monitoring as a result of characterization of the contaminant source and the environmental setting should be investigated for concentrations of methane and constituents during the initial monitoring phase.

Shallow borehole monitoring using a bar punch probe method or equivalent (See Section 11.6) is recommended. The bar punch is simply a steel or metal bar which is hand-driven or hammered to depths of 6 feet. Once this hole is made it is covered with a stopper or seal to confine the headspace in the hole. The hole should be allowed to equilibrate for up to an hour prior to sampling to provide sufficient time for subsurface gas to replace the air in the hole. The ease of installation of bar punch holes and the ability to obtain real-time direct measurements from field survey instruments combine to make this task a relatively simple operation. It should be recognized, however, that shallow borehole monitoring is a rapid screening method and therefore has its limitations. Two major limitations are that negative findings cannot assure the absence of a release at a greater depth and that air intrusions can dilute the sampling readings. See also Sections 9 (Soil) and 10 (Ground Water) for additional information.

The number of locations to monitor will vary from site to site. However, due to the ease of this operation, it is recommended that many locations be surveyed during the initial monitoring phase. Selection of locations along the perimeter of the unit of concern and at intervals of approximately 100 feet is an adequate initial approach. Individual site conditions and anomalies should be considered to determine whether the number of sampling locations should be increased or decreased. A large site with homogeneous subsurface conditions could require fewer sampling locations by increasing the distance between sampling points. A site with many subsurface anomalies, such as engineered barriers or varying soil strata, would require a greater number of sampling locations. In general, sampling locations should be established where conditions are conducive to gas migration, such as in sands, gravels and porous soils, and near engineered conduits (e.g., underground utility lines). The appropriate precautions should be taken when sampling near engineered conduits so as not to damage such property and to assure the safety of the investigative team and others.

The distance from the unit at which to sample can best be determined through consideration of site-specific characteristics (e.g., soil conditions), and can be aided by the use of the gas concentration contour map generated by the predictive model described in Appendix D. The shallow borehole survey should be fairly extensive, ranging from sampling locations very near the unit to locations at the property boundary and beyond.

11.4.4.2 Gas Monitoring Wells

Gas monitoring wells (See Section 11.6) should be installed to obtain data on subsurface gas concentrations at depths greater than the depth accessible with a bar punch probe. Wells should be installed to a depth equal to that of the unit. Multiple probe depths may be installed at a single location as illustrated in Figure 11-3. Where buried material is fairly shallow (e.g., <10-feet), single depth gas monitoring probes may be sufficient. When buried material exceeds this depth below ground, multiple depth probes should be installed.

The location and depth of gas monitoring wells should be based on the presence of highly permeable zones (e.g., dry sand or gravel), alignment with offsite structures, proximity of the waste deposit, areas where there is dead or unhealthy vegetation (that may be due to gas migration), and any engineered channels which would promote the migration of a subsurface gas release (e.g., utility lines). This information should be gathered during a review of subsurface conditions, as discussed previously. At a minimum, a monitoring well should be installed at the location(s) of expected maximum concentration(s), as determined or estimated during the initial monitoring phase.

Gas monitoring well installation usually requires the use of a drilling rig or power auger. Once a borehole has been drilled to the desired depth, the gas monitoring probes can be installed as illustrated in Figure 11-3. Additional information concerning the installation of subsurface gas monitoring wells is provided in Section 10 (Ground Water) and in Guidance Manual for the Classification of Solid Waste Disposal Facilities NTIS PB81-218505 (U.S. EPA, 1981).

Equilibration times of at least 24 hours should be allowed prior to collection of subsurface gas samples for analysis after well installation and between subsequent collection periods. Individual site characteristics or anomalies which can create significantly different subsurface conditions will require an increased number of wells to sufficiently determine the presence of gas migration. For example, if the predominant soil strata along one side of a unit changes from sandy clay to gravel, a well should be installed in both of these areas. Also, if the amount of gas producing

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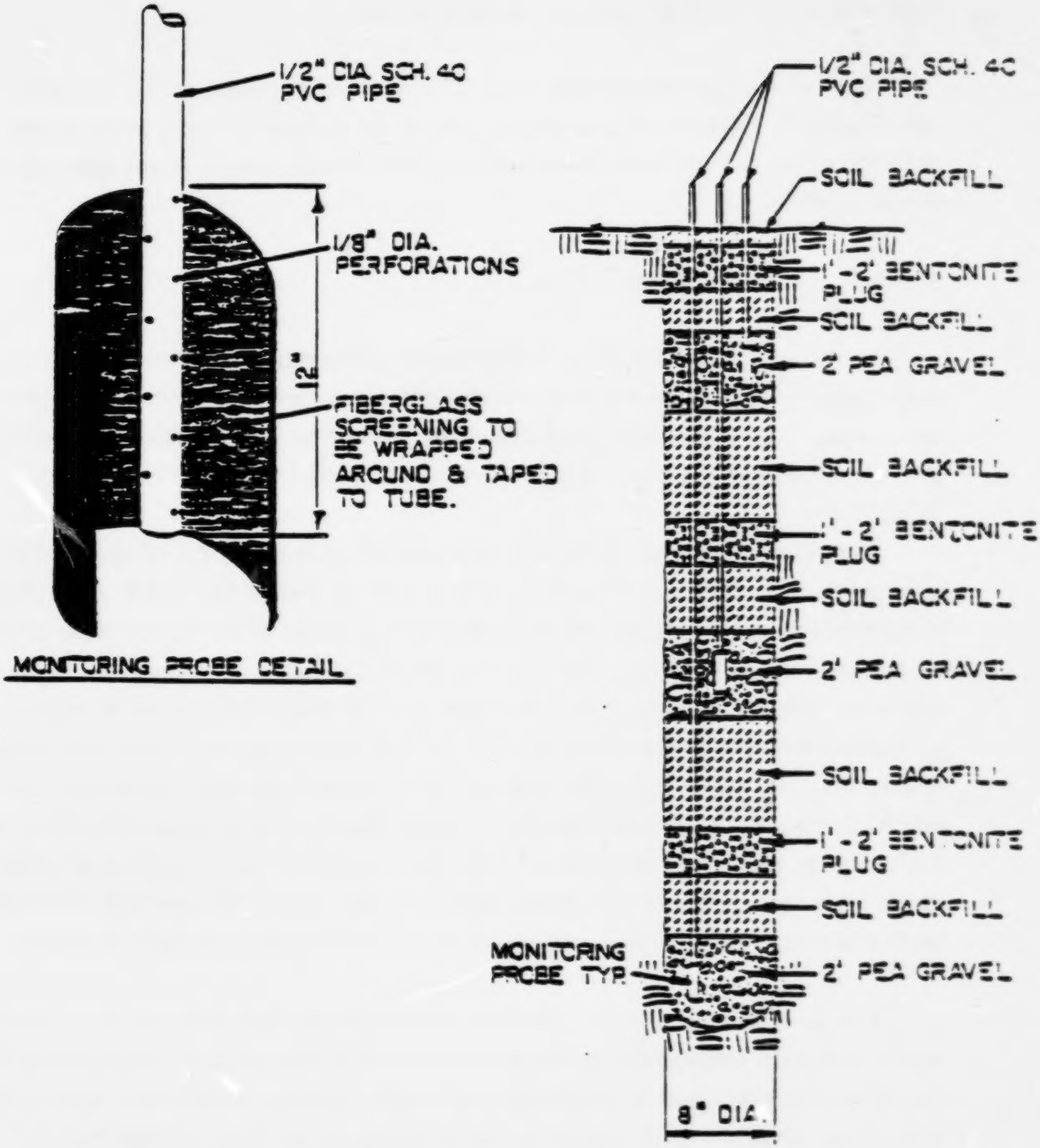
1/2" DIA. SCH. 40 PVC PIPE
1/8" DIA. PERFORATIONS
12"
FIBERGLASS SCREENING TO BE WRAPPED AROUND & TAPED TO TUBE.
MONITORING PROBE DETAIL
1/2" DIA. SCH. 40 PVC PIPE
SOIL BACKFILL
1' - 2' BENTONITE PLUG
SOIL BACKFILL
2' PEA GRAVEL
SOIL BACKFILL
1' - 2' BENTONITE PLUG
SOIL BACKFILL
2' PEA GRAVEL
SOIL BACKFILL
1' - 2' BENTONITE PLUG
SOIL BACKFILL
MONITORING PROBE TYP.
2' PEA GRAVEL
8" DIA.

Figure 11-3. Schematic of a Deep Subsurface Gas Monitoring Well

waste buried at the site varies greatly from one area to another, gas monitoring wells should be installed near each area of concern.

Subsurface gas monitoring may be done concurrently with ground-water investigations (Section 10), because results of subsurface gas monitoring may provide useful information for identifying the overall extent of any ground-water contamination.

11.4.4.3 Monitoring in Buildings

Monitoring should also be conducted in surrounding structures near the areas of concern, since methane and other subsurface gas constituents migrating through the soil can accummulate in confined areas. Use of an explosimeter for methane is the recommended monitoring technique (See Section 11.6).

Sampling should be conducted at times when the dilution of the indoor air is minimized and the concentration of soil gas is expected to be at its highest concentration. Optimal sampling conditions would be after the building has been closed for the weekend or overnight and when the soil surface outside the building and over the unit of concern has been wet or frozen for several days. These conditions will maximize the potential for lateral migration of gas into buildings rather than vertically into the ambient air. Recommended sampling locations within the building include basements, crawl spaces, and around subsurface utility lines such as sewer or electrical connections. Access conduits such as manholes or meter boxes are good sampling locations for water, sewer, or gas main connections. Methane and, if appropriate, individual constituents should be monitored for.

The threat of explosion from accumulation of methane within a building makes this monitoring activity important as well as dangerous. The monitoring of gas concentrations within buildings is a simple process involving a walk through inspection of areas with portable field instruments (e.g., explosimiter). Such measurements should begin during the initial monitoring phase. The importance of identifying potential releases to buildings warrants a complete inspection of all suspect areas. The inherent danger during these investigatons warrants adequate health and safety procedures (See Section 6).

If significant concentrations of methane or constituents are measured in surrounding structures during initial monitoring, subsequent monitoring may need to be expanded to include buildings at greater distances from the unit(s) of concern and to include additional constituents of concern. In addition, interim corrective measures should be considered.

Background indoor air quality levels may be accounted for during the collection and evaluation of the in-building sampling data. Background levels can be accounted for by identifying potential indoor air emission sources (e.g., use of natural gas as a fuel or wood paneling which has the potential for formaldehyde emissions). Further guidance on this subject is presented in the following reference:

> U.S. EPA. 1983. Guidelines for Monitoring Indoor Air Quality. EPA- 600/1-4 83-046. NTIS PB83-264465. Office of Research and Development. Washington, D.C. 20460.

11.4.4.4 Use of Predictive Models

In addition to monitoring potential gas releases using portable survey instruments, the owner or operator should consider the use of predictive models to estimate the configuration and concentration of gas releases. A subsurface gas predictive model has been developed by EPA to estimate methane gas migration from sanitary landfills. This model is based on site soil conditions, waste-related data, and other environmental factors.

As part of the initial monitoring phase, the model provided in Appendix D (or another appropriate predictive model after consultation with the regulatory agency), should be used to estimate the extent of subsurface gas migration. Results from this model can be used in determining appropriate monitoring locations. The methane gas migration model presented in Appendix D yields a methane concentration isopleth map of a release. The LEL and 0.25 LEL isopleths for methane should be mapped for the RFI. Because predictive models may not be sensitive to relevant site conditions, however, model results should be used cautiously for the monitoring program design and to supplement actual field data.

11.5 Data Presentation

Subsurface gas data collected during the RFI should be presented in formats that clearly define the composition and extent of the release. The use of tables and graphs is highly recommended. Section 5.2 provides a detailed discussion of data presentation methods.

11.5.1 Waste and Unit Characterization

Waste and unit characteristics should be presented as:

- Tables of waste constitutents and concentrations;
- Tables of relevant physical and chemical properties of waste and potential contaminants;
- Narrative description of unit dimensions, operations, etc.; and
- Topographical map and plan drawings of facility and surrounding areas.

11.5.2 Environmental Setting Characterization

Environmental characteristics should be presented as follows:

- Tabular summaries of annual and monthly or seasonal relevant climatic information (e.g., temperature, precipitation);
- Narratives and maps of soil and relevant hydrogeological characteristics such as porosity, organic matter content, and depth to ground water;
- Maps showing location of natural or man-made engineering barriers and likely migration routes; and
- Maps of geologic material at the site identifying the thickness, depth, and textures of soils, and the presence of saturated regions and other hydrogeological features.

11.5.3 Characterization of the Release

In general, release data should be initially presented in tabular form. To facilitate interpretation, graphs of concentrations of individual constituents plotted against distance from the unit should be used to identify migration pathways and areas of elevated concentrations. Concentration isopleth maps can also be drawn to identify the direction, depths, and distances of gas migration, and concentrations of constituents of concern. Specific examples of these and other data presentation methods are provided in Section 5. Methane concentrations should be presented in terms of the LEL and 0.25 LEL isopleths. Specific monitoring constituent concentrations should also be presented.

11.6 Field Methods

Field methods for subsurface gas investigations involve sample collection and analysis. Sample collection methods are discussed to summarize the monitoring techniques described above. Since subsurface gas monitoring is similar to air monitoring, the available methods for the collection and analysis of subsurface gas samples are presented here only in tabular format with further discussion in the air section of this document (Section 12). Tables 11-3 through 11-5 summarize various methodologies available to collect and analyze air samples. These methodologies range from real-time analyzers (e.g., methane explosimeters) to the collection of organic vapors on sorbents or whole air samples with subsequent laboratory analysis.

A portable gas chromatograph with a flame ionization detector (calibrated with reference to methane) can be used to measure methane concentrations in the field. Methane explosimeters (based on the principle of thermal conductivity) are also available and provide direct readings of LEL levels and/or percent methane present by volume.

TABLE 11-3
SUMMARY OF SELECTED ONSITE ORGANIC SCREENING METHODOLOGIES

Instrument or detector	Measurable parameters	Low range of detection	Comments
Century Series 100 or AID Model 500 (survey mode)	Volatile organic species	Low ppm	Uses Flame Ionization Detector (FID)
GfG Gas Etechonics (Methanometer)	Methane explosion potential	Low ppm	Sensitive to methane
National Mine Service Company	Methane explosion potential	Low ppm	Sensitive to methane
Mine Safety Appliances, Inc.	Methane explosion potential	Low ppm	Sensitive to methane

TABLE 11-4

SUMMARY OF CANDIDATE METHODOLOGIES FOR QUANTIFICATION OF VAPOR PHASE ORGANICS

Collection Techniques	Analytical Technique	Applicability[a]	Positive Aspects	Negative Aspects
1. Sorption onto Tenax-GC or carbon molecular sieve packed cartridges using low-volume pump	Thermal Desporption into GC or GC/MS	I	• adequate QA/QC data base • widely used on investigations around uncontrolled waste sites • wide range of applicability • µg/m³ detection limits • practicality for field use	• possibility of contamination • artifact formation problems • rigorous cleanup needed • no possibility of multiple analysis • low breakthrough volumes for some compounds
2. Sorption onto charcoal packed cartridges using low-volume pump	Desorption with solvent-analysis by GC or GC/MS	II	• large data base for various compounds • wide use in industrial applications • practical for field use	• problems with irreversible adsorption of some compounds • high (mg/m³) detection limits • artifact formation problems • high humidity reduces retention efficiency
3. Sorption onto polyurethane foam (PUF) using low-volume or high-volume pump	Solvent extraction of PUF; analysis by GC/MS	I, II, III	• wide range of applicability • easy to perclean and extract • very low blanks • excellent collection and retention efficiencies • reusable up to 10 times	• possibility of contamination • losses of more volatile compounds may occur during storage

TABLE 11-4 (continued)

SUMMARY OF CANDIDATE METHODOLOGIES FOR QUANTIFICATION OF VAPOR PHASE ORGANICS

Collection Techniques	Analytical Technique	Applicability[a]	Positive Aspects	Negative Aspects
4. Sorption on passive dosimeters using Tenax or charcoal as adsorbing medium	Analysis by chemical or thermal desorption followed by GC or GC/MS	I or II	• Samplers are small, portable, require no pumps • makes use of analytical procedures of known precision and accuracy for a broad range of compounds • $\mu g/m^3$ detection limits	• problems associated with sampling using sorbents (see #I and II) are present • uncertainty in volume of air sampled makes concentration calculations difficult • requires minimum external air flow rate
5. Cryogenic trapping of analytes in the field	Desorption into GC	II, III	• applicable to a wide range of compounds • artifact formation minimized • low blanks	• requires field use of liquid nitrogen or oxygen • sample is totally used in one analysis-no reanalysis possible • samplers easily clogged with water vapor • no large data base on precision or recoveries
6. Whole air sample taken in glass or stainless steel bottles	Cryogenic trapping or direct injection into GC or GC/MS (onsite or laboratory)	II, III	• useful for grab sampling • large data base • excellent long-term storage • wide applicability • allows multiple analyses	• difficult to obtain integrated samples • low sensitivity if preconcentration is not used
7. Whole air sample taken in Tedlar® Bag	Cryogenic trapping or director injection into GC or GC/MS (onsite or laboratory)	II, III	• grab or integrated sampling • wide applicability • allows multiple analyses	• long-term stability uncertain • low sensitivity if preconcentration is not used • adequate cleaning of containers between samples may be difficult

TABLE 11-4 (continued)

SUMMARY OF CANDIDATE METHODOLOGIES FOR QUANTIFICATION OF VAPOR PHASE ORGANICS

Collection Techniques	Analytical Technique	Applicability[a]	Positive Aspects	Negative Aspects
8. Dinitropheynlhydrazine Liquid Impinger Sampling using low-volume pump	HPLC/UV analysis	IV	• specific to aldehydes and ketones • good stability for derivatized compounds • low detection limits	• fragile equipment • sensitivity limited by reagent impurities • problems with solvent evaporation when long-term sampling is performed
9. Director introduction by probe	Mobile MS/MS	I, II, III, IV	• immediate results • field identification of air contaminants • allows "real-time" monitoring • widest applicability of any analytical method	• high instrument cost ($250K) • requires highly trained operators • grab samples only • no large data base on precision or accuracy

a Applicability Code

I Volatile, nonpolar organics (e.g., aromatic hydrocarbons, chlorinated hydrocarbons) having boiling points in the range of 80 to 200° C.

II Highly volatile, nonpolar organics (ie.g, vinyl chloride, vinylidene chloride, benzene, toluene) having boiling points in the range of -15 to + 120° C.

III Semivolatile organic chemicals (e.g., organochlorine pesticides and PCBs).

IV Aldehydes and ketone.

TABLE 11-5
TYPICAL COMMERCIALLY AVAILABLE SCREENING TECHNIQUES FOR ORGANICS IN AIR

Techniques	Manufacturer	Compounds Detected	Approximate Detection Limit	Comment
Gas Detection Tubes	Draeger Matheson (Kitagawa)	Various organics and inorganics	0.1 to 1 ppmv	Sensitivity and selectivity highly dependend on components of interest.
Continuous Flow Colorimeter	CEA Instruments, Inc.	Acrylonitrile, Formaldehyde, Phosgene, and	0.05 to 0.5 ppmx	Sensitivity and selectivity similar to detector tubes.
Colorimetric Tape Monitor	MDA Scientific	Toluene, diisocyanate, dinitrotoluene, phosgene, and various inorganics	0.05-0.5 ppmx	Sensitivity and selectivity similar to detector tubes.
Infrared Analysis	Foxboro/Wilkes	Most organics	1-10 ppmv	Some inorganic gases (H2), CO) will be detected and therefore are potential interferences.
FID (Total Hydrocarbon Analyzer)	Beckman MSA, Inc. AID, Inc.	Most organics	0.5 ppmv	Responds uniformly to most organic compounds on a carbon basis.
GC/FID (portable)	Foxboro/Century AID, Inc.	Same as above except that polar compounds may not elute from the column	0.5 ppmv	Qualitative as well as quantitative information obtained.
PID and GC/PID (portable)	HNU, Inc. AID, Inc. Photovac, Inc.	Most organic compounds can be detected with the exception of methane	0.1 to 100 ppbv	Selectivity can be adjusted by selections of lamp energy. Aromatics most readily detected.
GC/ECD (portable)	AID, Inc.	Halogenated and nitro substituted compounds	0.1 to 100 ppbv	Response various widely from compound to compound.
GC/FPD (portable)	AID, Inc.	Sulfur or phosphorus-containing compounds	10-100 ppbv	Both inorganic and organic sulfur or phosphorus compounds will be detected.
Chemiluminescent Nitrogen Detector	Antek, Inc.	Nitrogen-containing compounds	0.1 ppmv (as N)	Inorganic nitrogen compounds will interfere.

Table 11-3 provides a list of organic screening methodologies suited for detection of methane. Commercial monitoring equipment (direct reading) suitable for screening application are also available specifically for carbon dioxide, and sulfur dioxide. Similar field screening equipment are available for oxygen in order to check for the potential for intrusion of ambient air into the subsurface gas monitoring well. These screening monitors are available from most major industrial hygiene equipment vendors. Direct reading gas detection (e.g., draeger) tubes are also available for methane and other subsurface gas indicators for screening applications.

It is important that all monitoring procedures be fully documented and supported with adequate QA/QC procedures. Information should include: locations and depths of sampling points, methods used (including sketches and photographs), survey instruments used, date and time, atmospheric/soil temperature, analytical methods, and laboratory used, if any. Also see Section 4 (Quality Assurance and Quality Control).

The three basic monitoring techniques available for sampling subsurface gas; above ground air monitoring, shallow borehole monitoring, and gas well monitoring are summarized below.

11.6.1 Above Ground Monitoring

This technique consists of the collection of samples of the subsurface gas after it has migrated out of the soil or into engineered structures (e.g., within buildings or along under-ground utility lines.). Basically, there is no difference in the apparatus from that described for ambient air monitoring (Section 12). The locations at which sampling is conducted, however, are selected to focus on areas where gases might accumulate. Sampling methods can utilize various types and brands of portable direct-reading survey instruments (see Table 11-5). However, since methane gas is frequently the major component of the soil gas, those which are most sensitive to methane, such as explosimeters and FID organic vapor analyzers, are the preferred instruments. More selective air sampling methods are used, however, for constituent analyses (see Section 12 - Air Methods).

11.6.2 Shallow Borehole Monitoring

Shallow borehole monitoring involves subsurface gas monitoring to depths of up to 6 feet below the ground surface. Bar punches or metal rods which can be hand-driven or hammered into the ground are used to make boreholes from which gas samples are removed. Table 11-6 provides the basic procedure for shallow and deep subsurface monitoring techniques. Sample collection should follow the same methods employed during above ground monitoring.

Shallow borehole monitoring, as previously discussed, is a rapid screening method and, therefore, has its limitations. Two major limitations are that negative findings cannot assure the absence of a release at a greater depth and that air intrusion can dilute the measured concentration levels of the sample. Misleading results can also be obtained if the surface soil layer is contaminated (e.g., due to a spill).

11.6.3 Gas Well Monitoring

Monitoring gas within wells will involve either the lowering of a sampling probe (made of a nonsparking material) through a sealed cap on the top of the well to designated depths, or the use of fixed-depth monitoring probes (see Figure 11-3 and Table 11-6). The probe outlet is usually connected to the desired gas monitoring instrument. More information on gas well monitoring is provided in Sections 9 (Soil) and 10 (Ground Water).

Table 11-6

Subsurface Sampling Techniques

SHALLOW (Up to 6 ft deep)

- Select sampling locations based on soil data and existing monitoring data.
- Penetrate soil to desired depth. A steel rod 1/2 to 3/4 inch diameter and a heavy hammer are sufficient. A bar punch equipped with insulated handles is better for numerous holes. It is a small, hand operated pile driver with a sliding weight on the top. Hand augers may also be used.
- Insert inert (e.g., Teflon) tubing to bottom of hole. Tubing may be weighted or attached to a small diameter stick to assure that it gets to the bottom of the hole. Tubing should be perforated along bottom few inches to assure gas flow.
- Close top of hole around tubing using a gas impervious seal.
- Before sampling record well head pressure.
- Readings may be taken immediately after making the barhole.
- Attach meter or sampling pump and evacuate hole of air-diluted gases before recording gas concentrations or taking samples.
- When using a portable meter, begin with the most sensitive range (0-100 percent by volume of the lower explosive limit (LEL) for methane). If meter is pegged, change to the next least sensitive range to determine actual gas concentration.
- Tubing shall be marked, sealed, and protected if sampling will be done later.

Table 11-6 (Continued)

Subsurface Sampling Techniques

- If results are erratic the hole should be plugged and further readings taken a few minutes later.
- Monitoring should be repeated a day or two after probe installation to verify readings.

DEEP (More Than 6 ft deep)

- Same general procedures as above.
- Use portable power augers or truck-mounted augers.
- For permanent monitoring points, use rigid tubing (e.g., Teflon) and the general construction techniques shown in Figure 11-4.

CAUTION

- When using hand powered equipment, stop if any unusually high resistance is met. This resistance could be from a gas pipe or an electrical cable.
- Before using powered equipment, confirm that there are no underground utilities in the location(s) selected (see Appendix C - Geophysical Techniques).
- Use non-sparking equipment and procedures and monitor for methane explosive limits.

11.7 Checklist

RFI Checklist - Subsurface Gas

Site Name/Location ______________________________

Type of Unit ______________________________

1. Does waste characterization include the following information? (Y/N)
    - Physical form of waste ____
    - Chemical composition and concentrations ____
    - Presence of biodegradeable waste components ____
    - Quantities managed and dates of receipt ____
    - Location of wastes in unit ____
    - Waste material moisture content and temperature ____
    - Chemical and physical properties of constituents of concern ____

2. Does unit characterization include the following information? (Y/N)
    - Age of unit ____
    - Construction integrity ____
    - Presence of liner (natural or synthetic) ____
    - Location relative to ground-water table or bedrock or other confining barriers ____
    - Unit operation data ____
    - Presence of cover or other surface covering to impede vertical gas migration ____
    - Presence of gas collection system ____
    - Presence of surrounding structures such as buildings and utility conduits ____
    - Depth and dimensions of unit ____
    - Inspection records ____
    - Operation logs ____
    - Past fire, explosion, odor complaint reports ____

RFI Checklist - Subsurface Gas (Continued)

- Existing gas/ground-water monitoring data ____
- Presence of natural or engineered barriers near unit ____
- Evidence of vegetative stress ____

3. Does environmental setting information include the following information? (Y/N)
    - Definition of regional climate ____
    - Definition of site-specific meteorological conditions ____
    - Definition of soil conditions ____
    - Definition of site specific terrain ____
    - Identification of subsurface gas migration routes ____
    - Identification of location of engineered conduits ____
    - Identification of surrounding structures ____

4. Have the following data on the initial phase of the release characterization been collected? (Y/N)
    - Extent and configuration of gas plume ____
    - Measured methane and gaseous constituent concentration levels in subsurface soil and surrounding structures ____
    - Sampling locations and schedule ____

5. Have the following data on the subsequent phase(s) of the release characterization been collected? (Y/N)
    - Extent and configuration of gas plume ____
    - Measured methane and gaseous constituent concentration levels in subsurface soil and surrounding structures ____ ____
    - Sampling locations and schedule ____

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APPENDIX C

GEOPHYSICAL TECHNIQUES

APPENDIX C

GEOPHYSICAL TECHNIQUES

The methods presented in this Appendix have been drawn primarily from two sources. The first, Geophysical Techniques for Sensing Buried Wastes and Waste Migration (Technos, Inc., 1982) was written specifically for application at hazardous waste sites, and for an audience with limited technical background. All of the surface geophysical methods discussed below can be found in this document. The second, Geophysical Explorations (U.S. Army Corps of Engineers, Engineering Manual 1110-1-1802, 1979) is a more generic application-oriented manual which contains the borehole methods described in this section.

Caution should be exercised in the use of geophysical methods involving the introduction or generation of an electrical current, particularly when contaminants are known or suspected to be present which have ignitable or explosive properties. The borehole methods are of particular concern due to the possible build up of large amounts of explosive or ignitable gases (e.g., methane).

ELECTROMAGNETIC SURVEYS

The electromagnetic (EM)* method provides a means of measuring the electrical conductivity of subsurface soil, rock, and ground water. Electrical conductivity is a function of the type of soil and rock, its porosity, permeability, and the fluids which fill the pore space. In most cases the conductivity (specific conductance) of the pore fluids will dominate the measurement. Accordingly, the EM method is applicable both to assessment of natural geohydrologic conditions and to mapping of many types of contaminant plumes. Additionally, trench boundaries, buried wastes and drums, as well as metallic utility lines can be located with EM techniques.

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*The term "electromagnetic" has been used in contemporary literature as a descriptive term for other geophysical methods, including ground penetrating radar and metal detectors which are based on electromagnetic principles. However, this document will use electromagnetic (EM) to specifically imply the measurement of subsurface conductivities by low frequency electromagnetic induction. This is in keeping with the traditional use of the term in the geophysical industry from which the EM methods originated.

Natural variations in subsurface conductivity may be caused by changes in soil moisutre content, ground water specific conductance, depth of soil cover over rock, and thickness of soil and rock layers. Changes in basic soil or rock types, and structural features such as fractures or voids may also produce changes in conductivity. Localized deposits of natural organics, clay, sand, gravel, or salt- rich zones will also affect subsurface conductivity.

Many contaminants will produce an increase in free ion concentration when introduced into the soil or ground water systems. This increase over background conductivity enables detection and mapping of contaminated soil and ground water at hazardous waste sites. Large amounts of organic fluids such as diesel fuel can displace the normal soil moisture, causing a decrease in conductivity which may also be mapped, although this is not commonly done. The mapping of a plume will usually define the local flow direction of contaminants. Contaminant migration rates can be estimated by comparing measurements taken at different times.

The absolute values of conductivity for geologic materials (and contaminants) are not necessarily diagnostic in themselves, but the variations in conductivity, laterally and with depth, are significant. It is these variations which enable the investigator to rapidly find anomalous conditions (See Figure C-1).

At hazardous waste sites, applications of EM can provide:

- Assessment of natural geohydrologic conditions;
- Locating and mapping of burial trenches and pits containing drums and/or bulk wastes;
- Locating and mapping of plume boundaries;
- Determination of flow direction in both unsaturated and saturated zones;

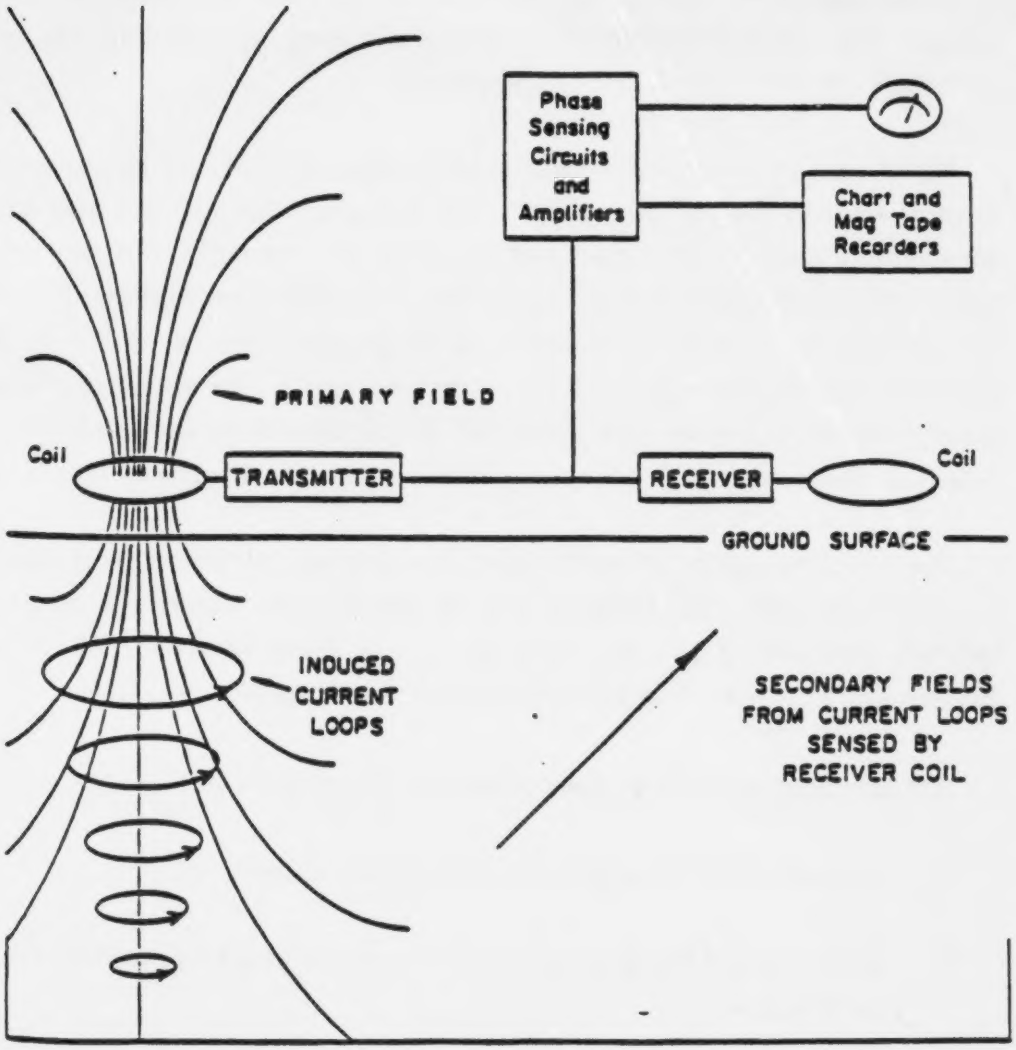
Phase
Sensing
Circuits
and
Amplifiers
Chart and
Mag Tape
Recorders
PRIMARY FIELD
Coil
TRANSMITTER
RECEIVER
Coil
GROUND SURFACE
INDUCED
CURRENT
LOOPS
SECONDARY FIELDS
FROM CURRENT LOOPS
SENSED BY
RECEIVER COIL

Figure C-1. Block diagram showing EM principle of operations.

- Rate of plume movement by comparing measurements taken at different times; and

- Locating and mapping of utility pipes and cables which may affect other geophysical measurements, or whose trench may provide a pathway for contaminant flow.

Chapter V of Geophysical Techniques for Sensing Buried Wastes and Waste Migration (Technos, Inc., 1982) should be consulted for further detail regarding use, capabilities, and limitations of electromagnetic surveys.

SEISMIC REFRACTION SURVEYS

Seismic refraction techniques are used to determine the thickness and depth of geologic layers and the travel time or velocity of seismic waves within the layers. Seismic refraction methods are often used to map depths to specific horizons such as bedrock, clay layers, and the water table. In addition to mapping natural features, other secondary applications of the seismic method include the locations and definition of burial pits and trenches.

Seismic waves transmitted into the subsurface travel at different velocities in various types of soil and rock, and are refracted (or bent) at the interfaces between layers. This refraction affects their path of travel. An array of geophones (transducers that respond to the motion of the ground) on the surface measures the travel time of the seismic waves from the source to the geophones at a number of spacings. The time required for the wave to complete this path is measured, permitting a determination to be made of the number of layers, the thicknesses of the layers and their depths, as well as the seismic velocity of each layer. The wave velocity in each layer is directly related to its material properties such as density and hardness. Figure C-2 depicts the seismic refraction technique.

Seismic refraction can be used to define natural geohydrologic conditions, including thickness and depth of soil and rock layers, their composition and physical properties, and depth to bedrock or the water table. It can also be used for the detection and location of anomalous features, such as pits and trenches and for evaluation of the depth of burial sites or landfills.

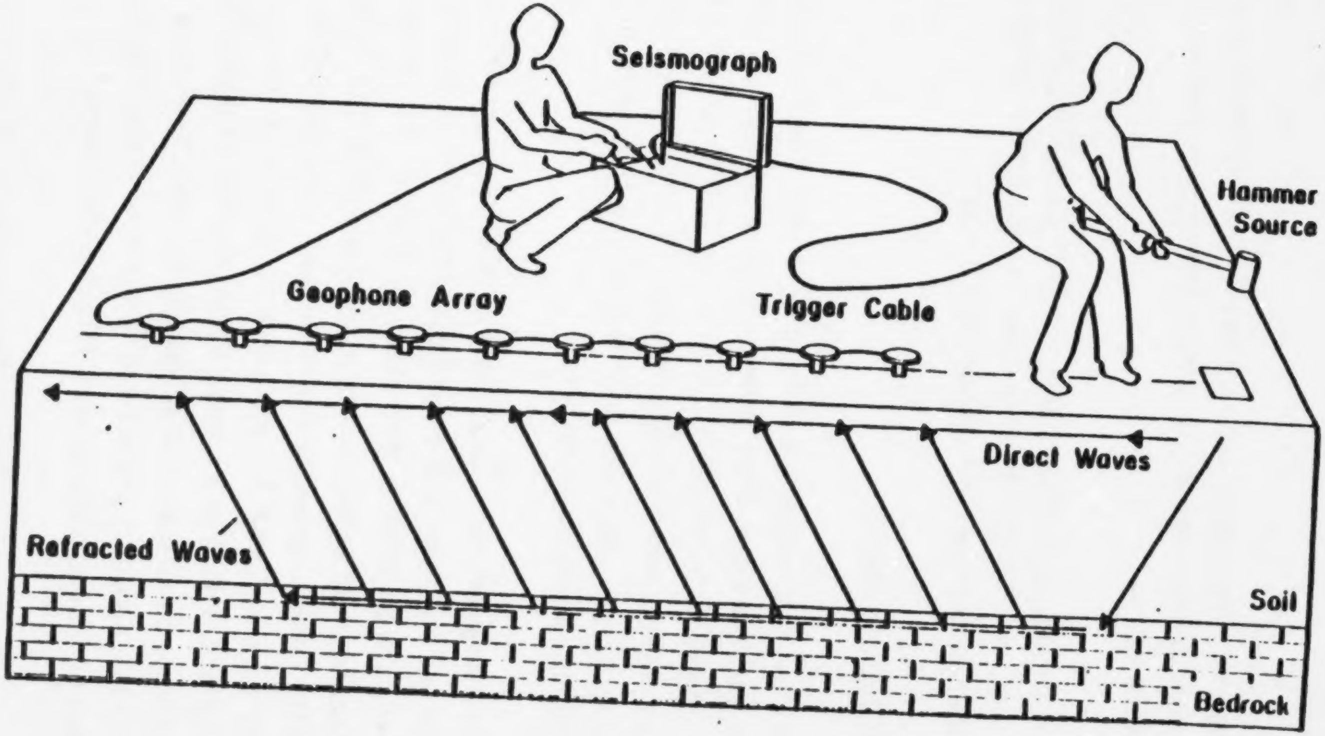
Seismograph
Hammer
Source
Geophone Array
Trigger Cable
Direct Waves
Refracted Waves
Soil
Bedrock

Figure C-2. Filed layout of a 12-channel seismograph showing the path of direct and refracted seismic waves in a two-layer soil/rock system.

Specific details regarding the use of seismic refraction surveys, and the capabilities and limitations of this method can be found in Chapter VII of Geophysical Techniques for Sensing Buried Wastes and Waste Migration (Technos, Inc., 1982).

RESISTIVITY SURVEYS

The resistivity method is used to measure the electrical resistivity of the geohydrologic section which includes the soil, rock, and ground water. Accordingly, the method may be used to assess lateral changes and vertical cross- sections of the natural geohydrologic settings. In addition, it can be used to evaluate contaminant plumes and locate buried wastes at hazardous waste sites. Figure C-3 is a graphical representation of the concept of a resistivity survey.

Applications of the resistivity method at hazardous waste sites include:

- Locating and mapping contaminant plumes;
- Establishing direction and rate of flow of contaminant plumes;
- Defining burial sites by:
    - locating trenches,
    - defining trench boundaries, and
    - determining the depths of trenches; and
- Defining natural geohydrologic conditions such as:
    - depth to water table or to water-bearing horizons; and
    - depth to bedrock, thickness of soil, etc.

Chapter VI of Geophysical Techniques for Sensing Buried Wastes and Waste Migration (Technos, Inc., 1982), discusses methods, use, capabilities, and limitations of the resistivity method.

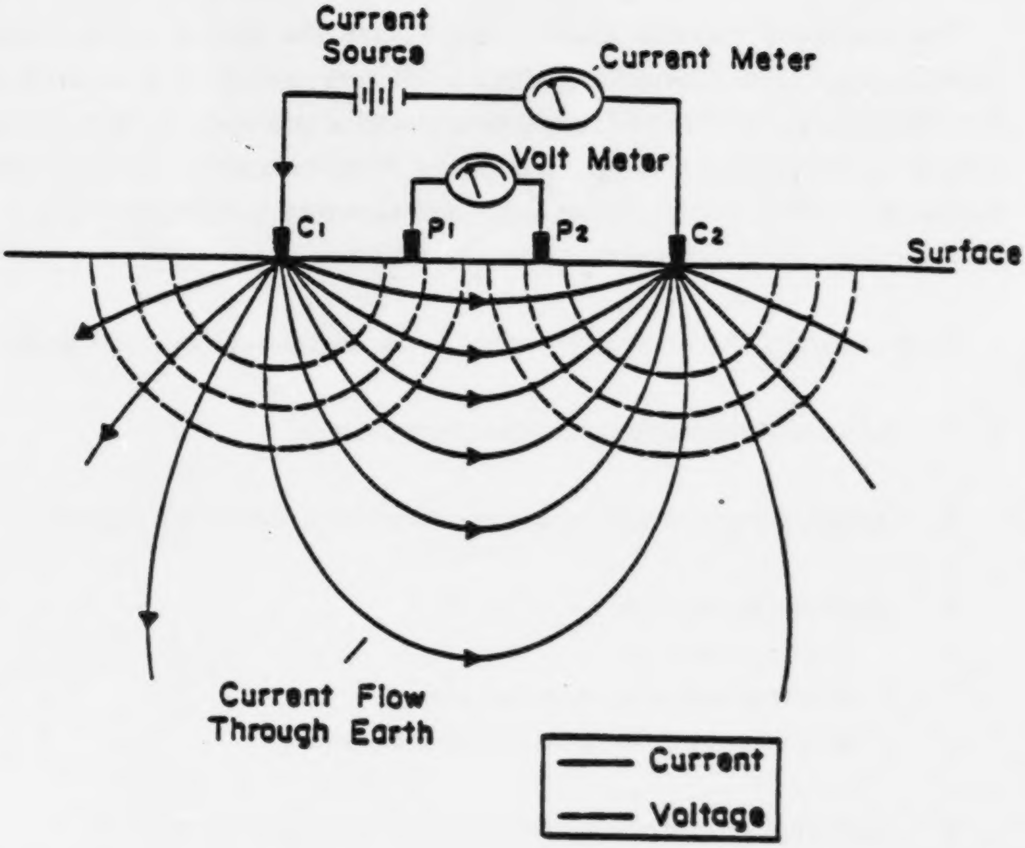
Current Source
Current Meter
Volt Meter
C1
P1
P2
C2
Surface
Current Flow Through Earth
Current
Voltage

Figure C-3. Diagram showing basic concept of resistivity measurement.

GROUND PENETRATING RADAR SURVEYS

Ground penetrating radar (GPR)* uses high frequency radio waves to acquire subsurface information. From a small antenna which is moved slowly across the surface of the ground, energy is radiated downward into the subsurface, then reflected back to the receiving antenna, where variations in the return signal are continuously recorded. This produces a continuous cross-sectional "picture" or profile of shallow subsurface conditions. These responses are caused by radar wave reflections from interfaces of materials having different electrical properties. Such reflections are often associated with natural geohydrologic conditions such as bedding, cementation, moisture and clay content, voids, fractures, and intrusions, as well as man-made objects. The radar method has been used at numerous sites to evaluate natural soil and rock conditions, as well as to detect buried wastes. Figure C-4 depicts the ground penetrating radar method.

Radar responds to changes in soil and rock conditions. An interface between two soil or rock layers having sufficiently different electrical properties will show up in the radar profile. Buried pipes and other discrete objects will also be detected.

Radar has effectively mapped soil layers, depth of bedrock, buried stream channels, rock fractures, and cavities in natural settings. Radar applications include:

- Evaluation of the natural soil and geologic conditions;

- Location and delineation of buried waste materials, including both bulk and drummed wastes;

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*GPR has been called by various names: ground piercing radar, ground probing radar, and subsurface impulse radar. It is also known as an electromagnetic method (which in fact it is); however, since there are many other methods which are also electromagnetic, the term GPR has come into common use today, and is used herein.

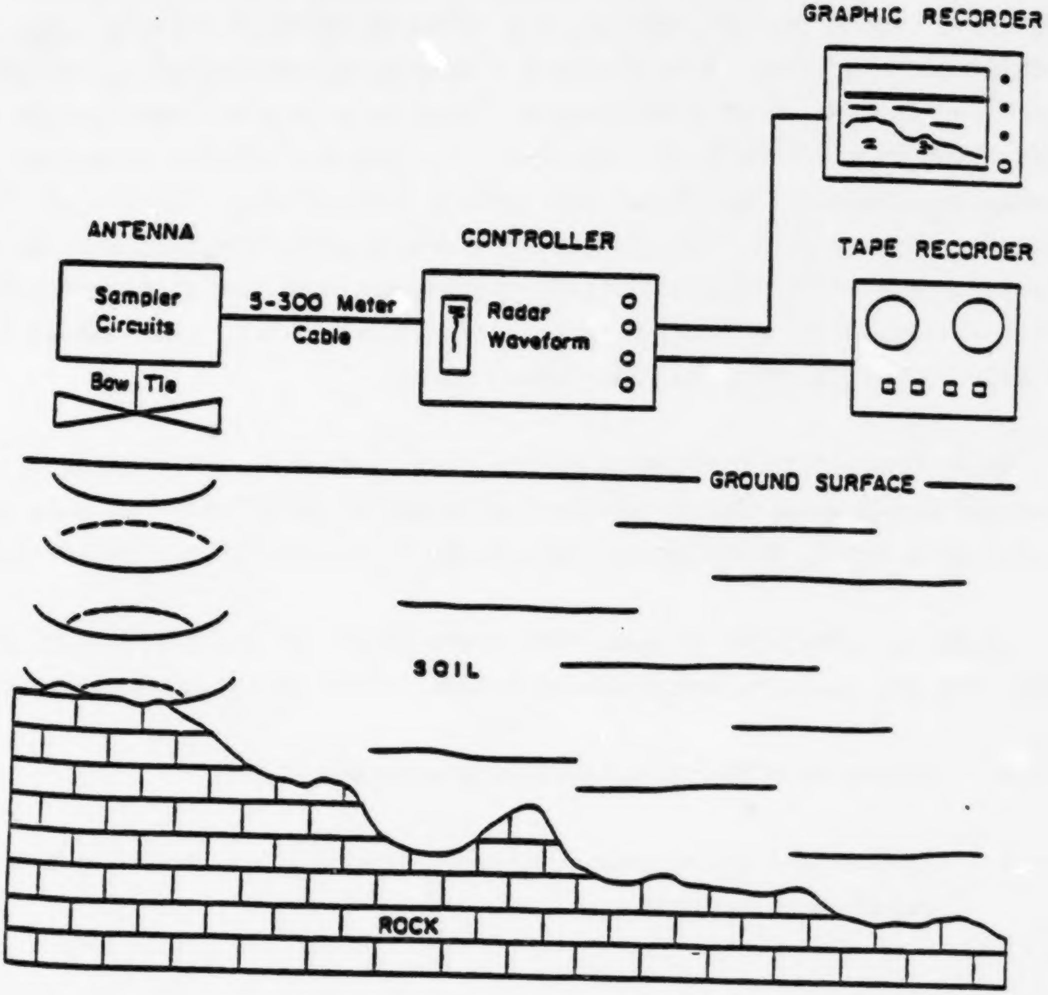

GRAPHIC RECORDER
ANTENNA
CONTROLLER
TAPE RECORDER
Sampler Circuits
5-300 Meter Cable
Radar Waveform
Bow Tie
GROUND SURFACE
SOIL
ROCK

Figure C-4. Block diagram of ground penetrating radar system.Radar waves are relfected from soil/rock interface.

- Location and delineation of contaminant plume areas; and
- Location and mapping of buried utilities (both metallic and nonmetallic).

In areas where sufficient ground penetration is achieved, the radar method provides a powerful assessment tool. Of the geophysical methods discussed in this document, radar offers the highest resolution. Ground penetrating radar methods are further detailed in Chapter IV of Geophysical Techniques for Sensing Buried Wastes and Waste Migration (Technos, Inc., 1982), as are this method's capabilities and limitations.

MAGNETOMETER SURVEYS

Magnetic measurements are commonly used to map regional geologic structure and to explore for minerals. They are also used to locate pipes and survey stakes or to map archeological sites. In addition, they are commonly used to locate buried drums and trenches.

A magnetometer measures the intensity of the earth's magnetic field. The presence of ferrous metals creates variations in the local strength of that field, permitting their detection. A magnetometer's response is proportional to the mass of the ferrous target. Typically, a single drum can be detected at distances up to 6 meters, while massive piles of drums can be detected at distances up to 20 meters or more. Figure C-5 shows the use of a magnetometer in detecting a buried drum.

Magnetometers may be used to:

- Locate buried drums;
- Define boundaries of trenches filled with ferrous containers;
- Locate ferrous underground utilities, such as iron pipes or tanks, and the permeable pathways often associated with them; and

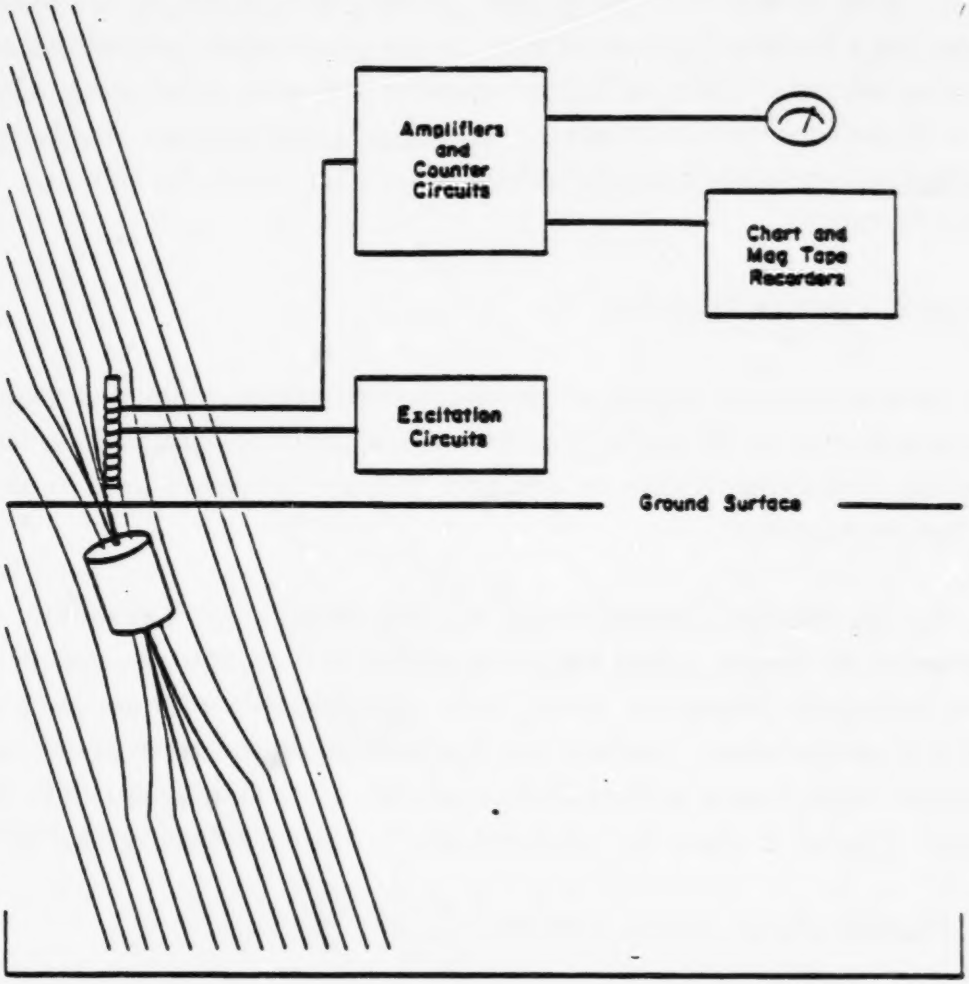

Amplifiers and Counter Circuits
Chart and Mag Tape Recorders
Excitation Circuits
Ground Surface

Figure C-5. Simplified block diagram of a magnetometer. A magnetometer senses change in the earth's magnetic field due to buried iron drum.

Electrical Surveys

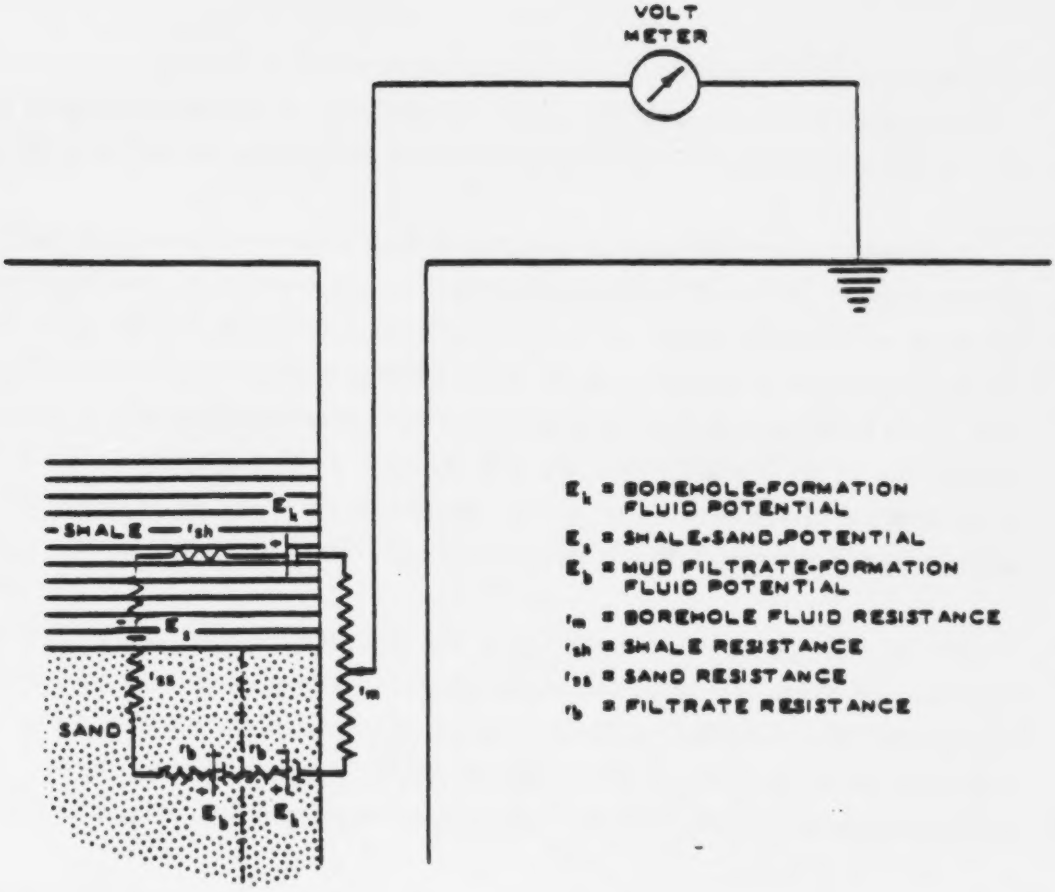
The two types of electrical subsurface surveys of geotechnical interest, both of which involve continuous logging with depth of the electrical characteristics of the borehole walls, are the spontaneous potential log and the borehole resistivity log.

The spontaneous potential log (also known as self potential) is a record of the variation with depth of naturally occurring electrical potentials (voltages) between an electrode at the depth in a fluid filled borehole and another at the surface.

The known origins for spontaneous potentials arise frm the relative mobility and concentrations of the different elemental ions dissolved in the borehole fluid and the fluid in adjacent strata. The electrochemical activities of the minerals in the strata also cause a component of the measured spontaneous potentials (Figure C-6). The relative senses and magnitudes of the several causes from which spontaneous potentials arise are affected by the nature of the borehole fluid, by the mineralogical characteristics of all the strata the borehole penetrates, and by the dissolved solid concentration in the ground water in all potential layers.

The second type of electric survey is the electrical resistivity log. The electrical resistivity of strata is one of the basic parameters that correlates to lithology and hydrology. Direct access to individual layers of the subsurface materials by means of the borehole is the primary advantage of electrical resistivity logging over the more indirect use of apparent electrical resistivity surveys from the surface.

Electrical current can be passed through in situ earth materials between two electrodes. Electric fields created within the three dimensional earth medium are related to the medium's structure and the nature of the aqueous fluid in the medium. Figure C-7 demonstrates the conceptual field configuration for borehole electrical resistivity survey.



VOLT
METER
E_k
SHALE
r_{sh}
E_s
r_{ss}
r_m
SAND
r_b
r_b
E_b
E_k
E_k = BOREHOLE-FORMATION FLUID POTENTIAL
E_s = SHALE-SAND POTENTIAL
E_b = MUD FILTRATE-FORMATION FLUID POTENTIAL
r_m = BOREHOLE FLUID RESISTANCE
r_{sh} = SHALE RESISTANCE
r_{ss} = SAND RESISTANCE
r_b = FILTRATE RESISTANCE

Figure C-6. Conceptual equivalent circuit for self-potential data (prepared by the Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi).

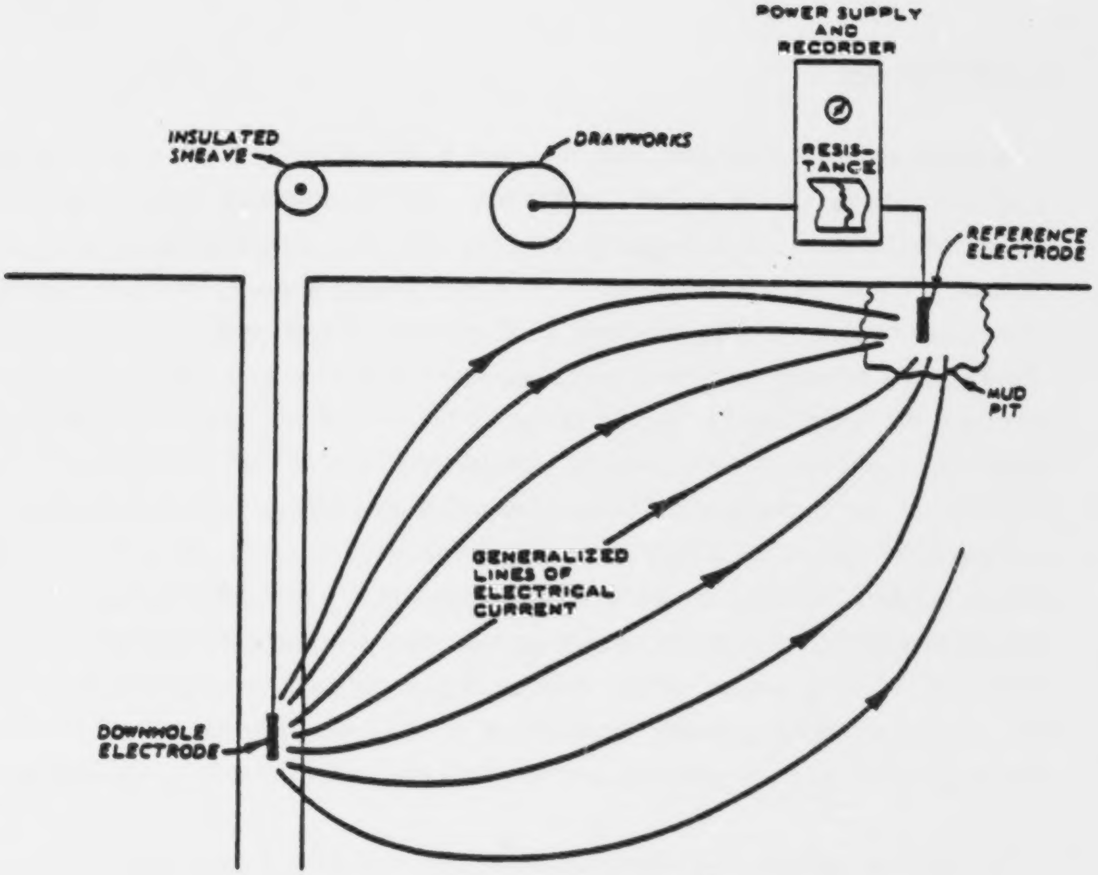

POWER SUPPLY AND RECORDER
RESIS-TANCE
INSULATED SHEAVE
DRAWWORKS
REFERENCE ELECTRODE
MUD PIT
GENERALIZED LINES OF ELECTRICAL CURRENT
DOWNHOLE ELECTRODE

Figure C-7. Single-point resistance log (prepared by the Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi).

Resistivity logging is a valuable tool in correlating beds from borehole to borehole. In addition, they can be used together with knowledge of ground water and rock matrix resistivities (obtained from samples) to calculate porosities and/or water saturations. Also, if porosity is known and a borehole temperature log is available, contaminant concentrations can be inferred by electrical resistivity variations.

Nuclear Logging

Nuclear borehole logging can be used quite effectively for borehole depths ranging from 10 to more than 1,000 feet. At considerable depths, as for large buried structures, nuclear logging is a very effective means of expanding a small number of data points obtained from direct measurements on core samples to continuous records of clay content, bulk density, water content, and/or porosity. The logs are among the simplest to perform and interpret, but the calibrations required for meaningful quantitative interpretations must be meticulously complete in attention to detail and consideration of all factors affecting nuclear radiation in earth materials. Under favorable conditions, nuclear measurements approach the precisions of direct density tests on rock cores. The gamma-gamma density log and the neutron water content log require the use of isotopic sources of nuclear radiation. Potential radiation hazards mandate thorough training of personnel working around these sources. Strict compliance with U.S. NRC Title 10, Part 20, as well as local safety regulations, is required. Additional information on natural gamma, gamma-gamma, and neutron gamma methods is provided below.

The natural gamma radiation tool is a passive device measuring the amount of gamma radiation naturally occurring in the strata being logged. The primary sources of radiation are trace amounts of the potassium isotope K^{40} and isotopes of uranium and thorium. K^{40} is most prevalent, by far, existing as an average of 0.012 percent by weight of all potassium. Because potassium is part of the crystal lattices of illites, micas, montmorillanites, and other clay materials, the engineering gamma log is mainly a qualitative indication of the clay content of the strata.

The natural gamma log is put to its simplest and most frequently used applications in qualitative lithologic interpretation (specifically identification of shale and clay layers) and bed correlations from hole to hole. Since clay fractions frequently reduce the primary porosity and permeability of sediments, inferences as to those parameters may sometimes be possible from the natural gamma log. Environmentally based surveys may utilize the log for tracing radioactive pollutants. If regulatory restrictions allow the use of radioactive tracers, the natural gamma log can be used to locate ground water flow paths. The natural gamma radiation level is also a correction factor to the gamma-gamma density log.

In the gamma-gamma logging technique, a radioactive source and detector are used to determine density variations in the borehole. An isotopic source of gamma radiation can be placed on the gamma radiation tool and shielded so that direct paths of that radiation from source to detector are blocked. The source radiation then permeates the space and materials near itself. As the gamma photons pass through the matter, they are affected by several factors among which is "Compton scattering." Part of each photon's energy is lost to orbital electrons in the scattering material. The amount of scattering is proportional to the number of electrons present. Therefore, if the portion of radiation able to escape through the logged earth materials without being widely scattered and de-energized is measured, then that is an inverse active measure of electron density. A schematic representation of the borehole gamma-gamma tool is shown in Figure C-8.

The neutron water detector logging method is much like the gamma-gamma technique in that it uses a radioactive source and detector. The difference is that the neutron log measures water content rather than density of the borehole material. A composite isotopic source of neutron radiation can be placed on a probe together with a neutron detector. A neutron has about the same mass and diameter as a hydrogen nucleus and is much lighter and smaller than any other geochemically common nucleus. Upon collision with a hydrogen nucleus the neutron loses about half its kinetic energy to the nucleus and is slowed down as well as scattered. Collision with one of the larger nuclei scatters the neutron but does not slow it. After a number of collisions with hydrogen nuclei, a neutron is slowed, or it is captured by a hydrogen atom and produces a secondary neutron emission of thermal energy plus a secondary gamma photon. Detectors can be "tuned" to be sensitive to the epithermal (slowed) neutron or to the thermal

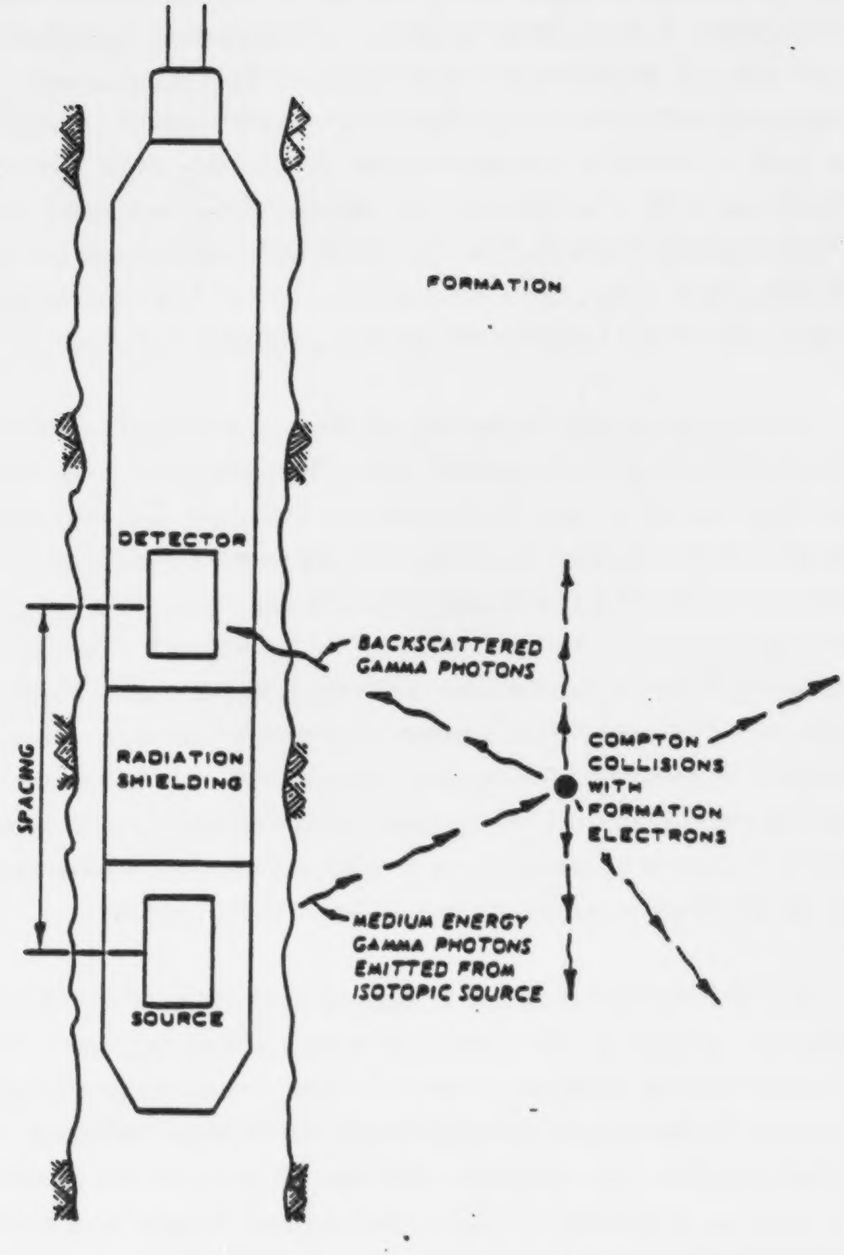

FORMATION
DETECTOR
BACKSCATTERED GAMMA PHOTONS
RADIATION SHIELDING
SPACING
COMPTON COLLISIONS WITH FORMATION ELECTRONS
MEDIUM ENERGY GAMMA PHOTONS EMITTED FROM ISOTOPIC SOURCE
SOURCE

Figure C-8. Schematic of the borehole gamma-gamma density tool (prepared by the Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi).

neutron or to the gamma radiation. One of these detectors plus the neutron source is then a device capable of measuring the amount of hydrogen in the vicinity of the tool. In the geologic environment, hydrogen exists most commonly in water (H2O) and in hydrocarbons. If it can be safely assumed that hydrocarbons are not present in appreciable amounts, then the neutron-epithermal neutron, the neutron-thermal neutron, and the neutron-gamma logs are measures of the amount of water present if the tool is calibrated in terms of its response to saturated rocks of various porosities.

The neutron log can be used for hole to hole stratigraphic correlation. Its designed purpose is to measure water quantities in the formation. Therefore, the gamma-gamma density, the neutron water detector, the natural gamma, and the caliper logs together form a "suite" of logs that, when taken together, can produce continuous interpreted values of water content, bulk density, dry density, void ratio, porosity, and pecent of water saturation.

Seismic Surveys

The principles involved in subsurface seismic surveys are the same as those discussed earlier under surface seismic surveys. The travel times for P- and S- waves between source and detector are measured, and wave velocities are determined on the basis of theoretical travel paths. These calculated wave velocities can then be used to complement and supplement other geophysical surveys conducted in the area of investigation.

Three common types of borehole seismic surveys are discussed in this section. They include Uphole and Downhole surveys, Crosshole Tests, and Vertical Seismic Surveys. The applications and limitations are discussed for each of these methods.

In the uphole and downhole seismic survey, a seismic signal travels between a point in a borehole and a point on the ground near the hole. In an uphole survey the energy source is in the borehole, and the detector on the ground surface; in a downhole survey, their positions are reversed. The raw data obtained are the travel times for this signal and distances between the seismic source and the geophones. A plot of travel time versus depth yields, from the slope of the curve, the average wave propagation velocities at various intervals in the borehole. Figure C-9 depicts a downhole seismic survey technique.

Uphole and downhole surveys are usually performed to complement other seismic tests and provide redundancy in a geophysical test program. However, because these surveys force the seismic signals to traverse all of the strata between the source and detector, they provide a means of detecting features, such as a low velocity layer underlying a higher velocity layer of a "blind" or "hidden" zone (a layer with insufficient thickness and velocity contrast to be detected by surface refraction).

Crosshole tests are conducted to determine the P- and S-wave velocity of each earth material or layer within the depth of interest through the measurement of the arrival time of a seismic signal that has traveled from a source in one borehole to a detector in another. The crosshole test concept is shown in Figure C-10.

In addition to providing true P- and S-wave velocities as a function of depth, their companion purpose is to detect seismic anomalies, such as a lower velocity zone underlying a higher velocity zone or a layer with insufficient thickness and velocity contrast to be detected by surface refraction seismic tests.

The vertical seismic profiling technique involves the recording of seismic waves at regular and closely spaced geophones in the borehole. The surface source can be stationary or it can be moved to evaluate seismic travel times to borehole geophones, calculate velocities, and determine the nature of subsurface features in the vicinity of the borehole.

Vertical seismic profiling surveys are different from downhole surveys in that they provide data on not only direct path seismic signals, but reflected signals as well. By moving the surface source to discrete distances and azimuths from the borehole, this method provides a means of characterizing the nature and configuration of subsurface interfaces (bedding, ground water table, faults), and anomalous velocity zones around the borehole.

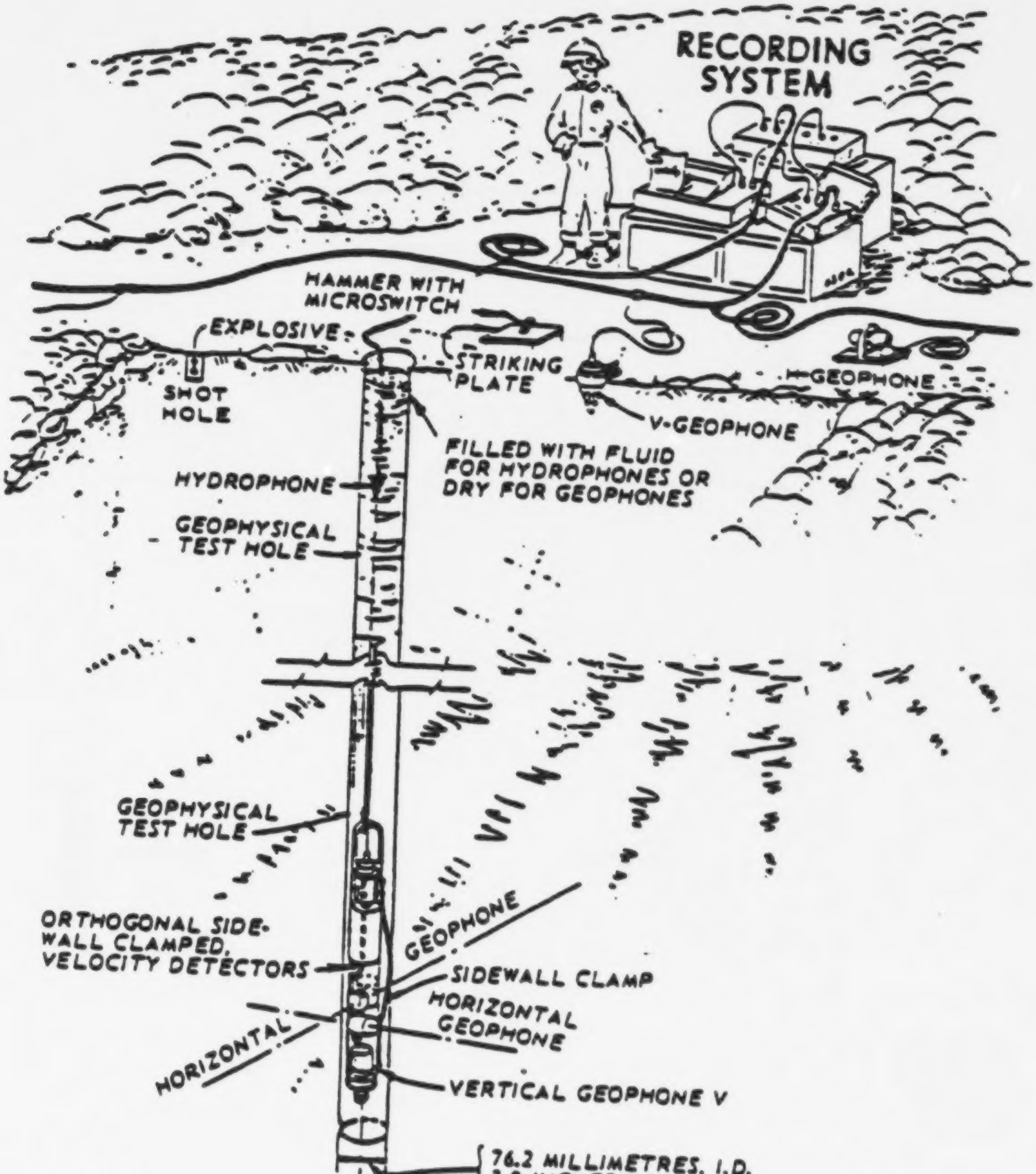

RECORDING SYSTEM
HAMMER WITH MICROSWITCH
EXPLOSIVE
STRIKING PLATE
H-GEOPHONE
SHOT HOLE
V-GEOPHONE
FILLED WITH FLUID FOR HYDROPHONES OR DRY FOR GEOPHONES
HYDROPHONE
GEOPHYSICAL TEST HOLE
GEOPHYSICAL TEST HOLE
ORTHOGONAL SIDE-WALL CLAMPED, VELOCITY DETECTORS
GEOPHONE
SIDEWALL CLAMP
HORIZONTAL GEOPHONE
HORIZONTAL
VERTICAL GEOPHONE V
76.2 MILLIMETRES, I.D.
3.0 INCHES, I.D.

Figure C-9. Downhole survey techniques for P-wave data (prepared by the Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi).

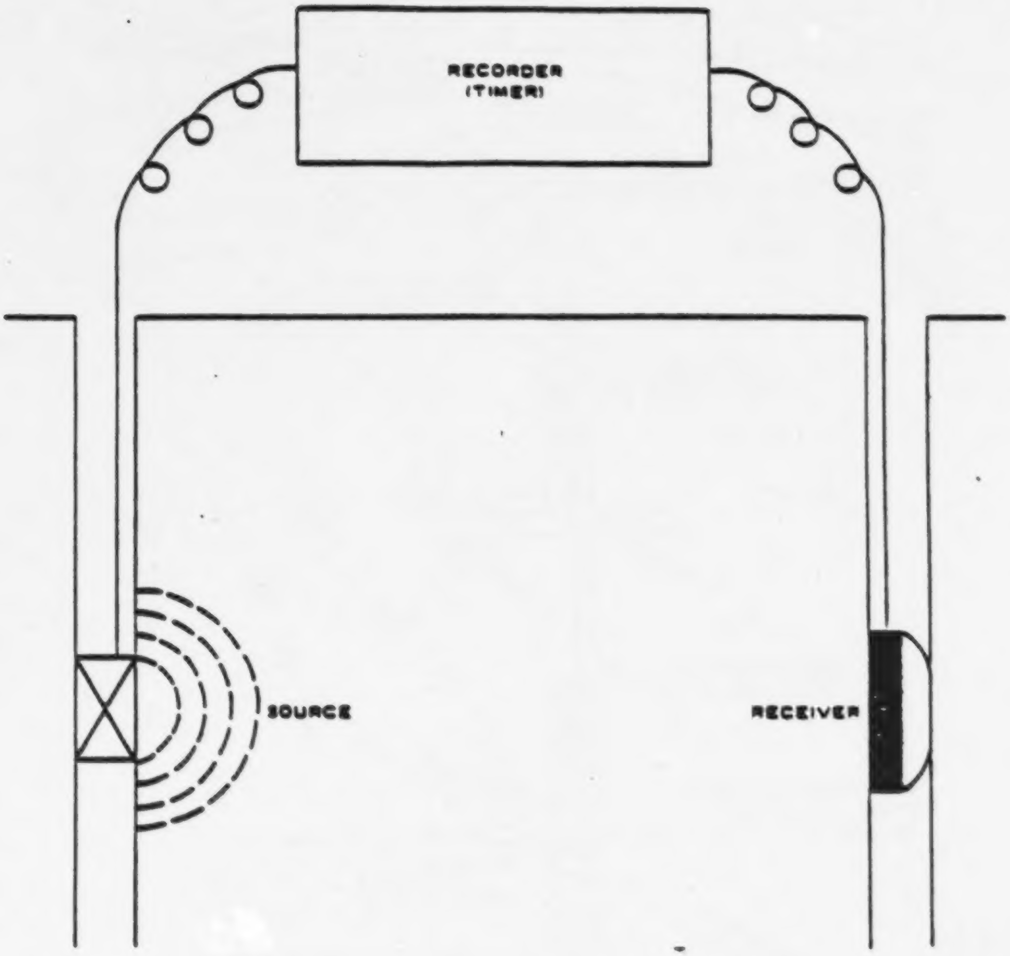

RECORDER
(TIMER)
SOURCE
RECEIVER

Figure C-10. Basic crosshole test concept (prepared by the Waterways Experiment Station, U.S. Army Corps of Engineers, Vicksburg, Mississippi).

The interpretation of processed vertical seismic profiling data is used in conjunction with surface seismic surveys as well as other geophysical surveys in the evaluation of subsurface lithology, stratigraphy, and structure. Vertical seismic profiling survey interpretations also provide a basis for correlation between boreholes.

Sonic Borehole Surveys

In this section, two types of continuous borehole surveys involving high frequency sound wave propagation are discussed. Sound waves are physically identical to seismic P-waves. The term sound wave is usually employed when the frequencies include the audible range and the propagating medium is air to water. Ultrasonic waves are also physically the same, except that the frequency range is above the audible range.

The Sonic borehole imagery log provides a record of the surface configuration of the cylindrical wall of the borehole. Pulses of high frequency sound are used in a way similar to marine sonar to probe the wall of the borehole and, through electronic and photographic means, to create a visual image representing the surface configuration of the borehole wall. The physical principle involved is wave reflection from a high impedance surface, the same principle used in reflection seismic surveying and acoustic subbottom profiling. The sonic borehole imagery logging concept is depicted in Figure C-11.

The sonic borehole imagery log can be used to detect discontinuities in competent rock lining the borehole. Varying lithologies, such as shale, sandstone, and limestone, can sometimes be distinguished on high quality records by experienced personnel.

Another method of sonic borehole logging is referred to as the continuous sonic velocity logging technique. The continuous sonic velocity logging device is used to measure and record the transit time of seismic waves along the borehole wall between two transducers as it is moved up or down the hole. A diagram of the continuous sonic velocity logging device is provided in Figure C-12.

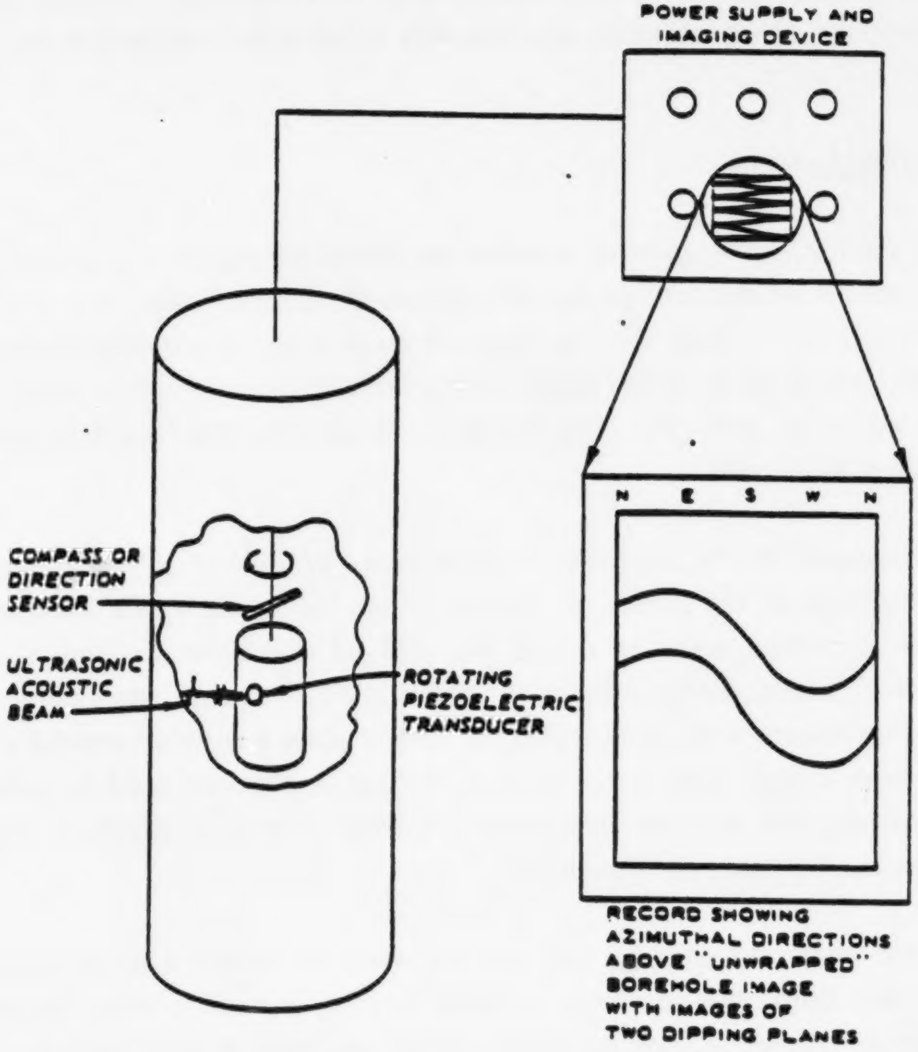

POWER SUPPLY AND IMAGING DEVICE
COMPASS OR DIRECTION SENSOR
ULTRASONIC ACOUSTIC BEAM
ROTATING PIEZOELECTRIC TRANSDUCER
N E S W N
RECORD SHOWING AZIMUTHAL DIRECTIONS ABOVE "UNWRAPPED" BOREHOLE IMAGE WITH IMAGES OF TWO DIPPING PLANES

Figure C-11. Sonic imagery logger (prepared by the Waterways Experiment Station, U.S. Army Corp of Engineers, Vicksburg, Mississippi).

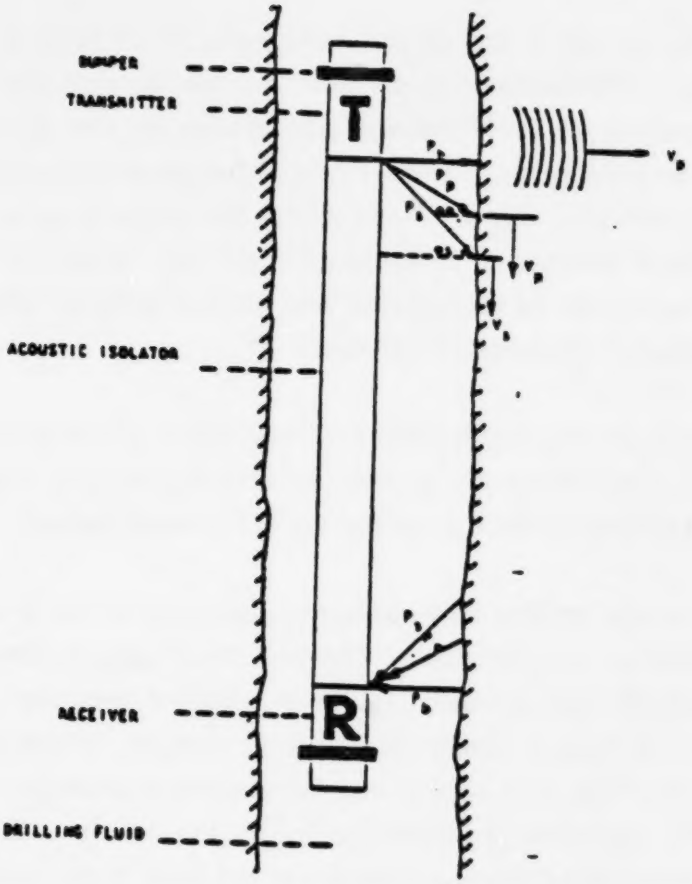

BUMPER
TRANSMITTER
T
V_p
V_p
V_s
ACOUSTIC ISOLATOR
RECEIVER
R
DRILLING FLUID

Figure C-12. Diagram of three-dimensional velocity tool (courtesy of Seismograph Service Corporation, Birdwell Division).

This subsurface logging method provides data on fractures and abrupt lithology changes along the borehole wall that can be effective in characterizing the nature of surrounding material as well as borehole correlation in lithology and structure.

Auxiliary Surveys

An auxiliary survey is the direct measurement of some parameter of the borehole or its contained fluid to provide information that will either permit the efficient evaluation of the lithology penetrated by the boring or aid in the interpretation or reduction of the data from other borehole logging operations. In most instances, auxiliary logs are made where the property recorded is essential to the quantitative evaluation of other geophysical logs. In some instances, however, the auxiliary results can be interpreted and used directly to infer the existence of certain lithologic or hydrologic conditions.

Discussed here are three different auxiliary logs; fluid temperature, caliper, and fluid resistivity, that are especially applicable to the logging methods discussed in this text. A description of each auxiliary log is presented below.

Temperature logs are the continuous records of the temperature encountered at successive elevations in a borehole. The two basic types of temperature logs are standard (gradient) and differential. Both types of logs rely upon a downhole probe, containing one or more temperature sensors (thermistors) and surface electronics to monitor and record the temperature changes encountered in a borehole. The standard temperature log is the result of a single thermistor continuously sensing the thermal gradient of the fluid in the borehole as the sonde is raised or lowered in the hole. The differential temperature log depicts the difference in temperature over a fixed interval of depth in the borehole by employing two thermistors spaced from one to several feet apart or through use of a single thermistor and an electronic memory to compare the temperature at one depth with that of a selected previous depth.

Temperature logs provide useful information in both cased and uncased borings and are necessary for correct interpretation of other geophysical logs (particularly resistivity logs). Temperature logs can also be used directly to indicate the source and movement of water into a borehole, to identify aquifers, to locate zones of potential recharge, to determine areas containing wastes discharged into the ground, and to detect sources of thermal pollution. The thermal conductivity and permeability of rock formations can be inferred from temperature logs as can be the location of grout behind casing by the presence of anomalous zones of heat buildup due to the hydration of the setting cement.

The caliper log is a record of the changes in borehole casing or cavity size as determined by a highly sensitive borehole measuring device. The record may be presented in the form of a continuous vertical profile of the borehole or casing wall, which is obtained with normal or standard caliper logging systems, or as a horizontal cross section at selected depths, used for measuring voids or large subsurface openings. There are two basic methods of obtaining caliper logs. One technique utilizes mechanically activated measuring arms or bown springs, and the other employs piezoelectric transducers for sending and receiving a focused acoustic signal. The acoustic method requires that the hole be filled with water or mud, but the mechanical method operates equally well in water, mud, or air. Reliable mechanically derived caliper logs can be obtained in small (2 in.) diameter exploratory borings as well as large (36 in.) inspection or access calyx-type borings.

Caliper or borehole diameter logs represent one of the most useful and possibly the simplest of all techniques employed in borehole geophysics. They provide a means for determining inhole conditions and should be obtained in all borings in which other geophysical logs are contemplated. Borehole diameter logs provide information on subsurface lithology and rock quality. Borehole diameter varies with the hardness, fracture frequency, and cementation of the various beds penetrated. Borehole diameter logs can be used to accurately identify zones of enlargement (washouts) or construction (swelling), or to aid in the structural evaluation of an area by the accurate location of fractures or solution openings, particularly in borings where core loss has presented a problem. Caliper logs also are a means of identifying the more porous zones in a boring by locating the intervals in which excessive mud filter cake has built up on the walls of the borehole. One of the major uses of standard or borehole caliper logs is to provide information by which other geophysically derived raw data logs can be corrected for borehole diameter effects. This is particularly true for such nonfocused logs as those obtained in radiation logging or the quantitative evaluation of flowmeter logs or tracer and water quality work where inhole diameters must be considered. Caliper logs also can be useful to evaluate inhole conditions for placement of water well screens or for the selection of locations of packers for permeability testing.

The fluid resistivity log is a continuous graphical record of the resistivity of the fluid within a borehole. Such records are made by measuring the voltage drop between two closely spaced electrodes enclosed within a downhole probe through which a representative sample of the borehole fluid is channeled. Some systems, rather than recording in units of resistivity, are designed to provide a log of fluid conductivity. As conductivity is merely the reciprocal of resistivity, either system can be used to collect the information on inhole fluid required for the correct interpretation of other downhole logs.

The primary use of fluid resistivity or conductivity logs is to provide information for the correct interpretation of other borehole logs. The evaluation of nuclear and most electrical logs requires corrections for salinity of the inhole fluids, particularly when quantitative parameters are desired for determining porosity from formation resistivity logs.

APPENDIX D

SUBSURFACE GAS MIGRATION MODEL ADAPTED FROM

GUIDANCE MANUAL FOR THE CLASSIFICATION OF SOLID WASTE DISPOSAL FACILITIES

U.S. EPA, 1981

APPENDIX D

SUBSURFACE GAS MIGRATION MODEL

METHANE MIGRATION DISTANCE PREDICTION CHARTS

Migration distance charts have been developed to estimate methane distances and to plan the monitoring program. The basic methane migration distance prediction chart and appropriate corrective factor charts were produced by imposing a set of simplifying assumptions on a general methane migration computer model. These charts are based on a number of assumptions that were made to produce them. Case Study Number 9 (Volume IV) illustrates the use of the Subsurface Gas Migration Model.

To illustrate the use of the charts, an example landfill is shown in Figure D-1 along with two cross-sections. Conditions along each side of the waste deposit are typical conditions that could be encountered. A similar sketch or plan of a facility being evaluated should be prepared. The land use within 1/4-mile of the solid waste limits, including offsite and facility structures, should be on the map. The property boundaries and solid waste deposit limits should also be plotted, as has been done in Figure D-1.

Additional data needs are:

1. The age of the site from the initial deposit of organic waste in years;
2. The average elevation of the bottom of the solid waste;
3. Natural boundaries and topography around the site; and
4. The average elevation below the solid waste of a gas impervious boundary such as unfractured rock.

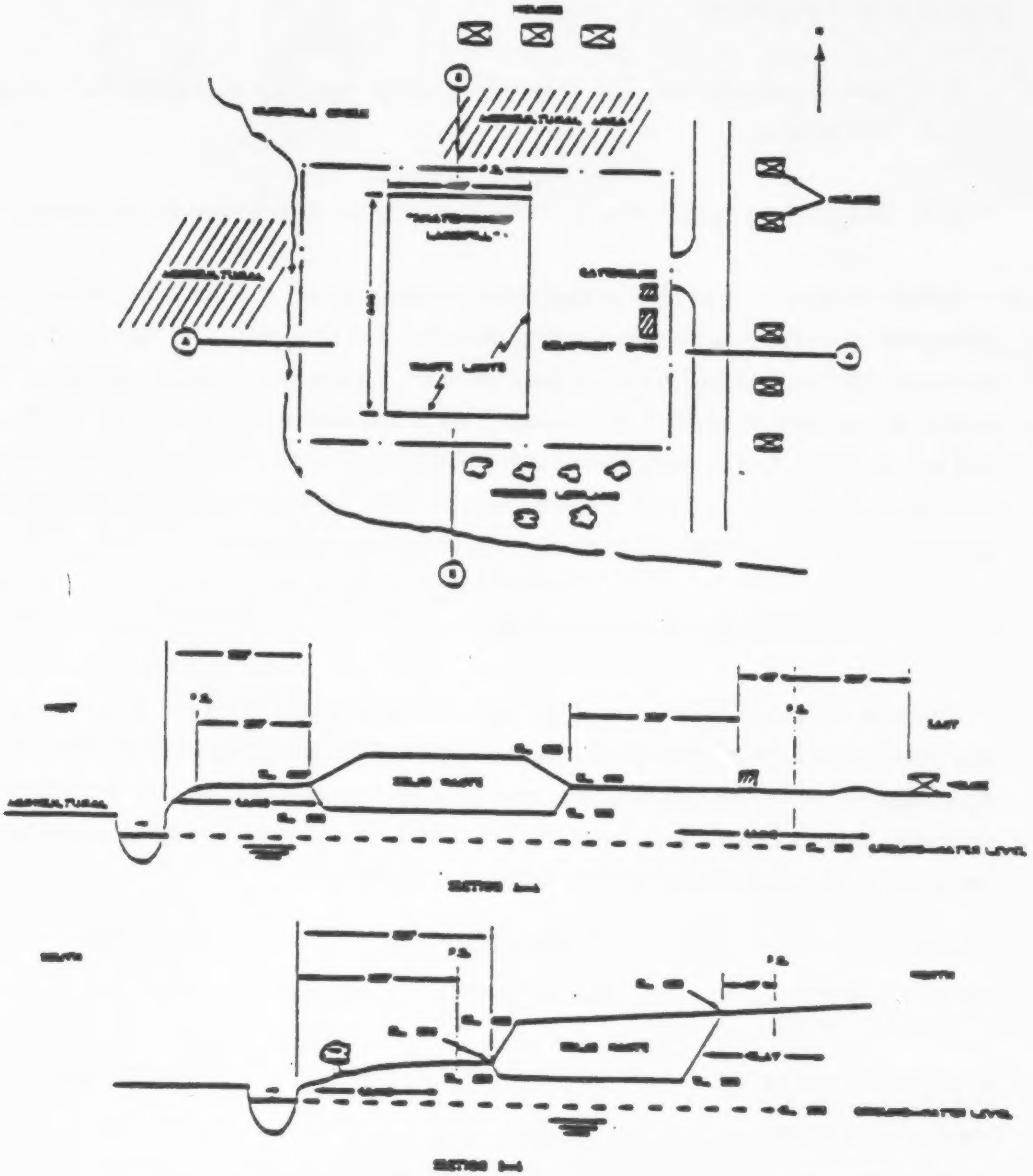

HOUSES
AGRICULTURAL AREA
AGRICULTURAL
WASTE LIMITS
GATEHOUSE
EQUIPMENT SHED
SOLID WASTE
GROUNDWATER LEVEL
CLAY
SOLID WASTE
GROUNDWATER LEVEL

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Figure D-1. Example landfill (not to scale).

Two calculations of migration distance from the waste boundary are needed for each side of the landfill:

1. The 5 percent (Lower Explosion Limit or LEL) distance for property boundaries.
2. The 1.25 percent (1/4 of the LEL) distance for onsite facility structures.

After preparation of the sketch and cross-sections, the determination of the estimated migration distances begins with the use of Figure D-2 for the 5 percent methane (LEL) migration distance and for the 1.25 percent (1/4 LEL) distance. These distances are then modified, if necessary, with the corrective factors for each depth and surrounding soil surface permeability (Figures D-3 and D-4). The final distances of migration for each side of the landfill can then be plotted on the landfill sketch for comparison to property boundary and structures locations.

UNCORRECTED MIGRATION DISTANCES

The use of Figure D-2 requires the age of the site and the type of soil extending out from each side of the solid waste deposit. The graph is entered with the site age, moving up to the appropriate soil type and methane concentration (1.25 or 5 percent). Interpolations between the sand and clay lines on the graph can be made for other soils, using the following general guidance:

Soil Name	USCS Classification	Chart Use
Clean (no fines) gravels and sands	GW, GP, SW, SP	Sand
Silty gravels and sands, silt, silty and sandy loam, organic silts	GM, SM, ML, OL, MH	Interpolate
Clayey gravels and sands, lean, fat, and organic clays	GC, SC, CL, CH, OH	Clay

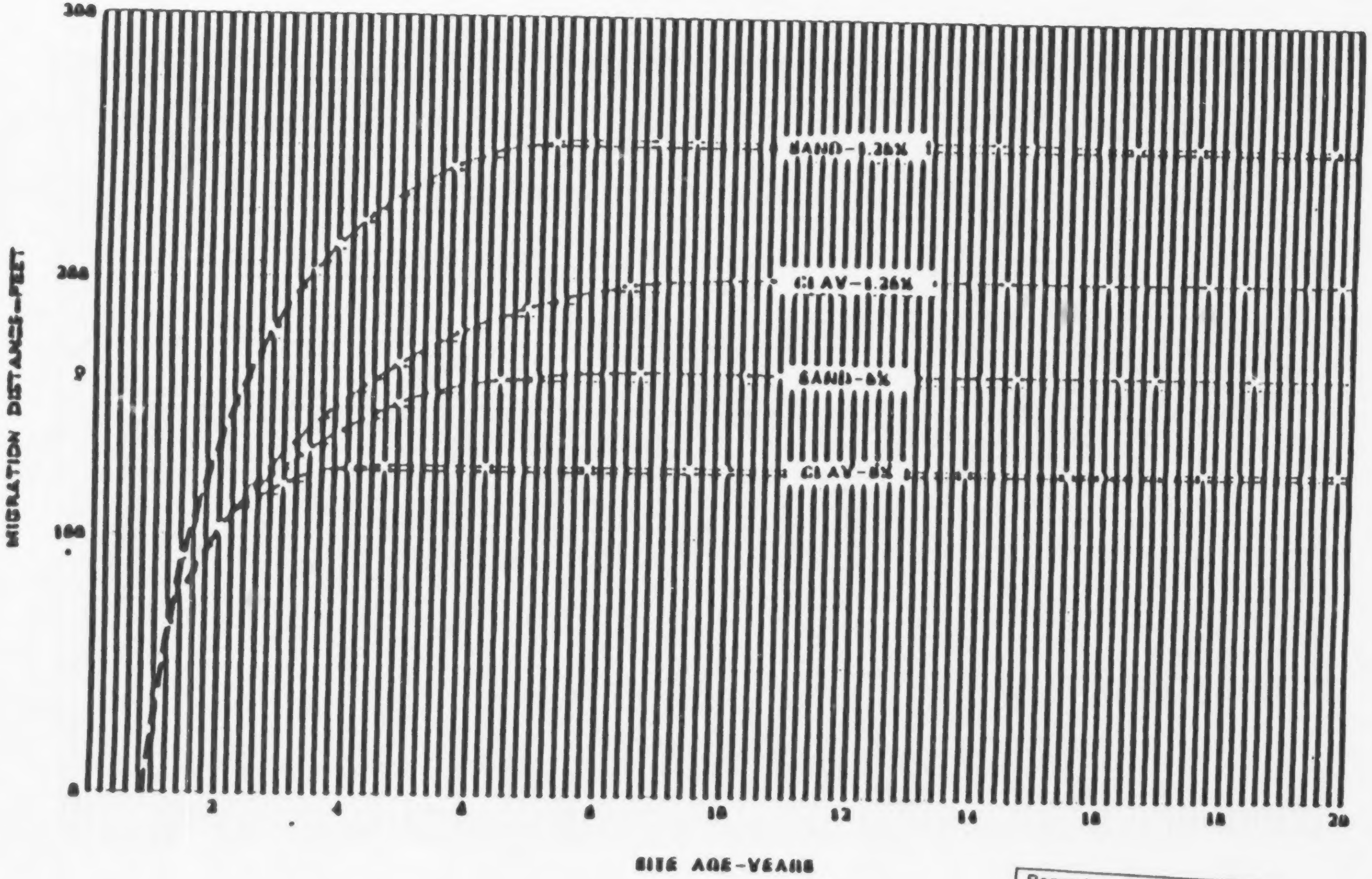

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Figure D-2. Five Percent and 1.25 percent methane migration distance.

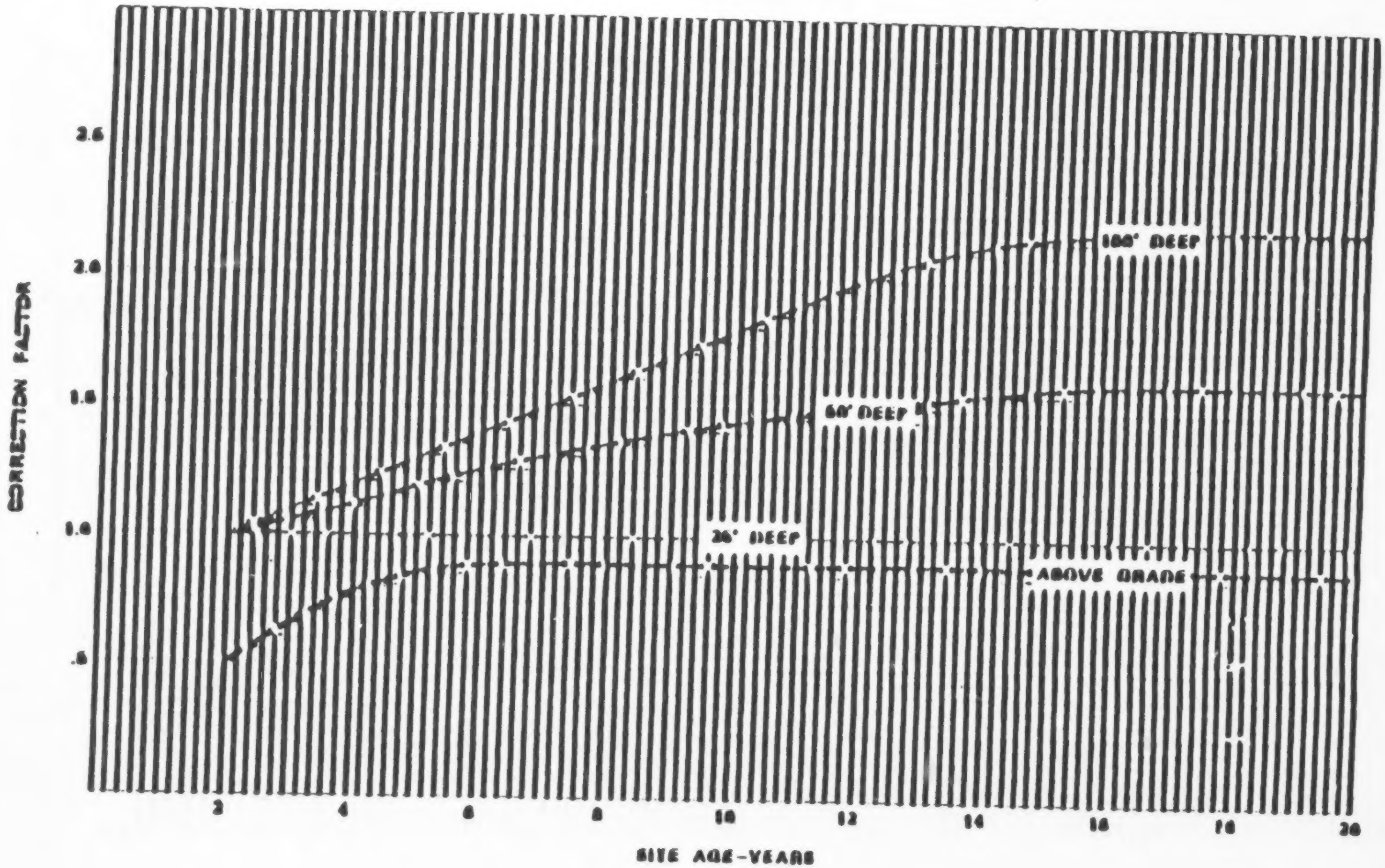

Figure D-3. Correction factors for landfill depth below grade.

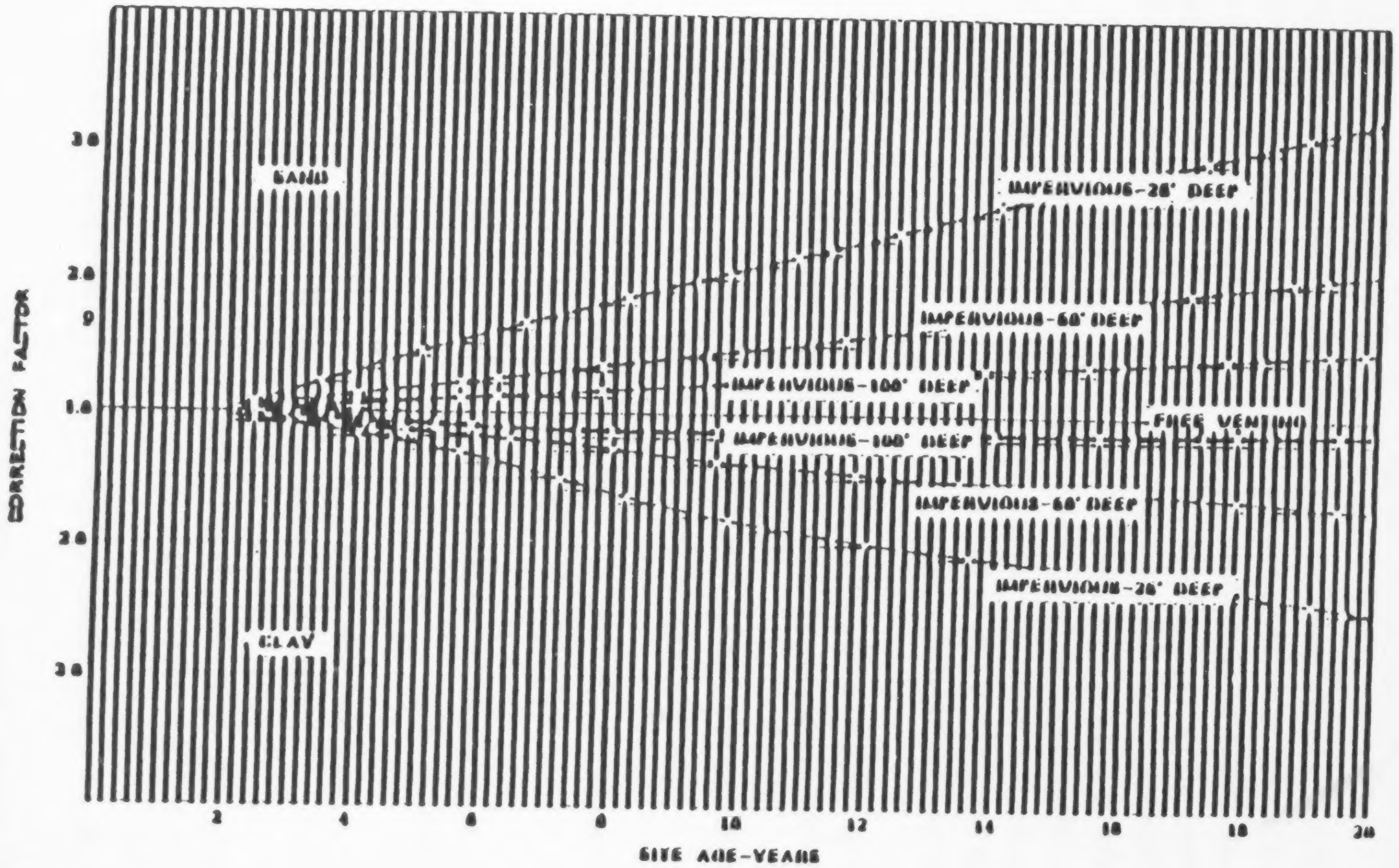

Figure D-4. Correction factors for soil surface venting condition around landfill.

The uncorrected migration distance from the solid waste limit can then be read on the left for the appropriate site age and soil type.

If the soil along a given boundary is stratified and the variability extends from the waste deposit to the property boundary, the most permeable unsaturated thickness should be used in entering the charts. For example, if dry, clean sand underlies surficial silty clays, the uncorrected migration distance should be obtained using the sand line of the chart. If there are questions as to the extent of particular soils along a boundary, helpful information might be obtained from Soil Conservation Services (SCS) Soil Survey Maps or the landfill operator. Field inspection, SCS maps, and permit boring information are sufficient. Additional borings are not necessary as this is only a ranking procedure. Where there is doubt, use the most permeable soil group present.

For the example landfill in Figure D-1, the uncorrected 5 percent methane migration distances for a 10-year old landfill would be (Figure C-2):

Section A-A: East side, 10 years, sand = 165'
West side, 10 years, sand = 165'

Section B-B: South side, 10 years, sand = 165'
North side, 10 years, clay = 130'

The corresponding uncorrected distances for the 1.25 percent methane migration would be:

Section A-A: East side, 10 years, sand = 225'
West side, 10 years, sand = 135'

Section B-B: South side, 10 years, sand = 255'
North side, 10 years, clay = 200'

The depth to corrective mulitpliers for the example sites would be:

Section A-A: East side, 10 years, 20' deep = 1.0
West side, 10 years, 20' deep = 1.0

Section B-B: South side, 10 years, 10' deep = 0.95
North side, 10 years, 50' deep = 1.4

VENTING CONDITIONS CORRECTION

The corrective factors for the surrounding soil venting conditions are obtained using the chart in Figure D-4. This chart is based on the assumption that the surrounding surficial soil is impervious 100 percent of the time. Thus, the value read from the chart must be adjusted, based on the percentage of time the surrounding surficial soil is saturated or frozen and the percentage of land along the path of gas migration from which gas venting to the atmosphere is blocked all year (asphalt or concrete roads or parking lots, shallow perched ground water, surface water bodies not interconnected to ground water). The totally impervious corrective factor is only used when the landfill is entirely surrounded at all times by these conditions. Both time and area adjustments are necessary, and the percentages are additive. Estimates to the nearest 20 percent are sufficient. An adjusted corrective factor is obtained by entering the chart with site age and obtaining the totally impervious corrective factor for the appropriate depth and soil type and then entering this value in the following equation:

Adjusted corrected factor = [(Impervious corrective factor)-1)]
x [5 of impervious time or area] + 1

When free venting conditions are prevalent most of the year, simply use 1.0 (no correction). For depths less than 25 feet deep, use the 25 foot value. For the example site, the adjusted corrective factors for frozen or wet soil conditions 50 percent of the year are:

Section A-A: East side (ignore narrow road, sand 20' deep, 10 years old) = (2.1-1)(0.50) + 1 = 1.55

West side (sand 20' deep, 10 years old) = (2.1-1)(0.50) + 1 = 1.55

Section B-B: South side (sand, 10′ deep, = (2.1-1)(0.50) + 1 = 1.55
10 years old)

North side (clay, 50′ deep, = (1.4-1)(0.50) + 1 = 1.2
10 years old)

Once the surface venting factors have been tabulated as in Table D-1, the corrective distance can be obtained by multiplying across the chart for each side of the landfill. These values can then be plotted on the scale plan to describe contours of the 5 percent and 1.25 percent methane concentrations or simply compared to the distance from the waste deposit to structures of concern (Figure D-5).

Table D-1. METHANE DISTANCE TABULATING FORM

Landfill Side	Methane Concentration	Uncorrected Distance	Correction for Depth	Correction for Venting	Corrected Distance
E	5%	165′	X 1.0	X 1.55	= 256′
	1.25%	255′	X 1.0	X 1.55	= 395′
W	5%	165′	X 1.0	X 1.55	= 256′*(225′ max.)
	1.25%	255′	X 1.0	X 1.55	= 395′*(225′ max.)
S	5%	165′	X 0.95	X 1.55	= 243′*(225′ max.)
	1.25%	255′	X 0.95	X 1.55	= 375′*(225′ max.)
N	5%	130′	X 1.4	X 1.2	= 218′
	1.25%	200′	X 1.4	X 1.2	= 336′

* When these distances are plotted on the landfill sketch, they exceed the distance to the creek, which acts as a barrier to the gas migration. Thus the distance to the creek is the maximum migration distance.

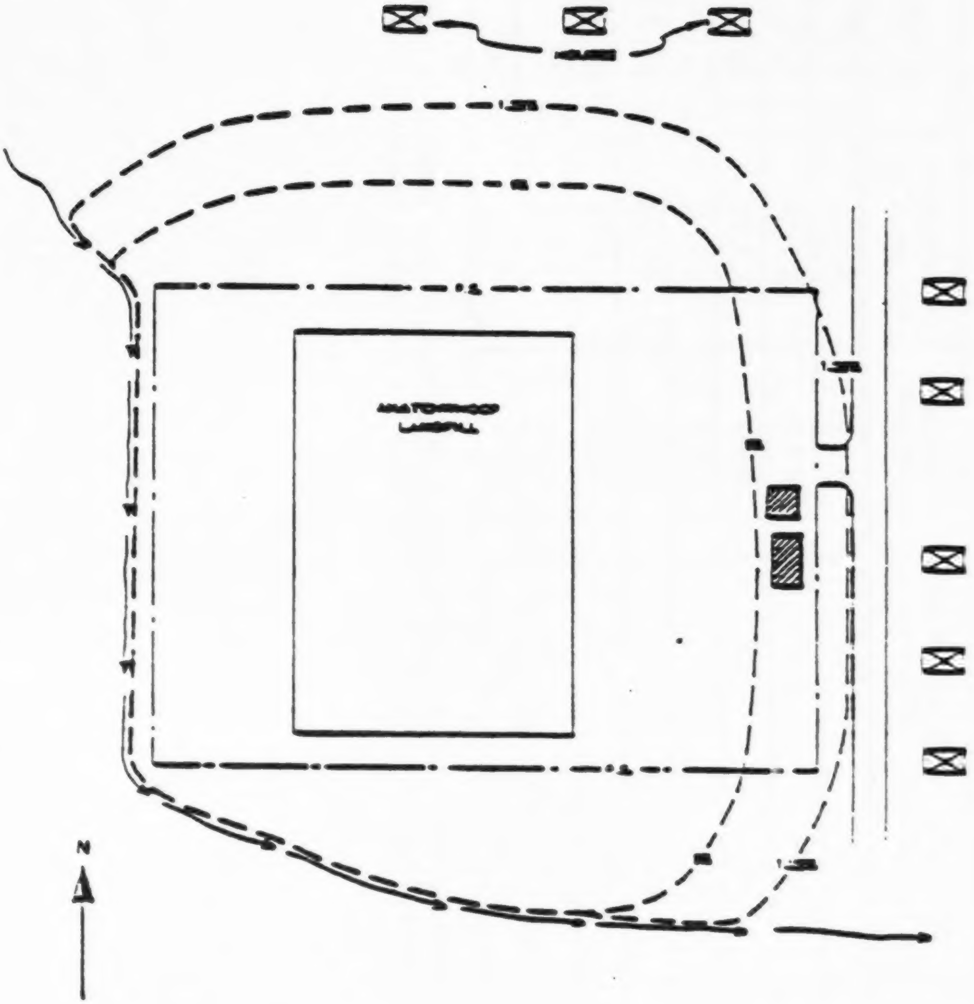

Figure D-5. Example landfill methane conditions.